Pathways towards a European Low Emission Society
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EUCALC

Policy Brief No. 9
February 2020

Pathways towards a fair and just net-zero emissions Europe by 2050

Insights from the EUCalc for carbon mitigation strategies

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Pathways towards a fair and just net-zero emissions Europe by 2050
Insights from the EUCalc for carbon mitigation strategies

Web site for further information: www.european-calculator.eu

Lead authors:
Alexandre Strapasson, Onesmus Mwabonje, Jeremy Woods, Gino Baudry[1]
Contributions by all EUCalc consortium members[2]

Coordination: Imperial College London

Editing and design: T6 Ecosystems srl

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Contact: *Onesmus Mwabonje, Room 403, Weeks Building, 16 Prince's Gardens, London SW7 1NE, United Kingdom. Email: o.mwabonje@imperial.ac.uk*

[1] See information on the authors at the end of this document.
[2] See full list of EUCalc consortium partners at the end of this document.

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Abbreviation list

BECCS – bioenergy with carbon capture and storage

BEV – battery-electric vehicle

BAU – Business as usual

BF-BOF – blast furnace – basic oxygen furnace

Bio-CCS – bioenergy with carbon capture and storage

Bio-CCU – bioenergy with carbon capture and use

CAP – Common Agricultural Policy

CC – carbon capture

CCS – carbon capture and storage

CCU – carbon capture and use

CDB - Convention on Biological Diversity

CGE – Computable General Equilibrium

CHP – combined heat and power

CO_2 – carbon dioxide

CO_2eq – carbon dioxide equivalent

CSP – concentrating solar power

°C – degrees celsius

DH – district heating

DRI – direct reduction of iron

EAF – electric arc furnaces

EJ – exajoule

€ - euros (currency)

EU – European Union

EUCalc – European Calculator

EULUF – EU Land Use Futures

EVs – electric vehicles

FCEV – fuel-cell electric vehicle

g - grams

GDP – Gross Domestic Product

GHG – greenhouse gas

GTAP – Global Trade Analysis Project

GW – gigawatt

ha – hectare

ICE – internal combustion engine

IIASA – International Institute for Applied Systems Analysis

IPCC – Intergovernmental Panel on Climate Change

kcal – kilocalories

kg - kilogram

km - kilometer

kWh – kilowatt-hour

LDVs – light-duty vehicles

lge – liters gasoline equivalent

LSU – livestock unit

LULUCF - Land use, land-use change, and forestry

m^2 – square meter

m^3 – cubic meter

MJ – megajoule

MJ/tkm – Mega Joules per tonne kilometre

Mt – megatons

MW – megawatt

µm – micrometer

NDC – Nationally Determined Contribution

PHEV – plug-in hybrid vehicle

$PM_{2.5}$ – particulate matter with diameter of less than 2.5 microns

PV – photovoltaics

ROW – rest of the world (outside EU)

SSP - Shared Socio-Economic Pathway

TPE – Transition Pathways Explorer

UK – United Kingdom

UNFCCC - United Nations Framework Convention on Climate Change

WACC – Weighted Average Cost of Capital

Headlines

- Achieving socially just and sustainable transition to a net-zero emissions Europe by 2050 requires urgent and substantive changes in the use of technology and the behavioural choices of its people.
- These changes will be pervasive, covering all sectors of the economy, from transport, manufacturing, agriculture and power generation. The choices we make as individuals and as national governments of services and goods we produce and consume, e.g. the foods we grow and eat, the sizes of our households and how we heat and cool them, our mobility and in our trading relationships with the rest of the world, are key determinants of successfully meeting the climate challenge.
- It is possible to achieve a net-zero greenhouse gas emission in Europe by 2050, in time to meet global climate targets, but it requires unprecedented levels of innovations in technologies and in the adoption of sustainable lifestyles, diets and land use.
- Avoiding confounding carbon leakage: the international trade balance (imports vs. exports) in the EU has and will continue to have a significant impact on internal EU and external (rest of the world) greenhouse gas emissions, materially affecting the EU's timeline to achieving net zero and globally effective climate mitigation.
- Policies that support the accelerated decoupling of economic growth from greenhouse gas emissions are needed along with incentives for the rest of the world to decarbonise if confounding leakage is to be avoided.
- No single sector can, by itself, materially reduce or sequester greenhouse gases; however, actions affecting the carbon stocks on land and the greenhouse gas emissions from agriculture are urgently required.
- Systemic changes at personal, local, national and regional levels are all important and publicly acceptable policies for transitioning to a net-zero emissions society are fundamental in order to meet the EU climate change targets.
- Tools, such as the EUCalc Transition Pathways Explorer, are needed to help decision makers navigate the vast option space and derive transition pathways that are fair, just, publicly acceptable and ultimately sustainable.

The EUCalc model and the Transition Pathways Explorer

The EUCalc model user interface - the Transition Pathways Explorer - is a tool that allows users to build a pathway to a net-zero carbon future at European and Member State level. Its scientific mission is to provide a sophisticated, yet accessible, model to fill the gap between integrated climate-energy-economy models and the practical needs of decision-makers. The model relates emission reduction with human lifestyles, the exploitation and/or conservation of natural resources, job creation, energy production, agriculture, costs, etc. in one highly integrative approach and tool which enables decision-makers to get real-time policy support underpinned by comprehensive trade-off analyses.

Politicians, innovators and investors can use the EUCalc Transition Pathways Explorer to create their own pathways to a low-carbon future online, in real-time and together. This tool can help policy makers in the EU28 + Switzerland explore the routes they can take to delivering climate protection, whilst securing energy and other important policy priorities.

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1 Context

The objective of this policy brief is to offer some key insights from the European Calculator (EUCalc) in order to help inform policy makers, business leaders and NGOs concerned with climate change mitigation.

It provides answers to some of the key questions related to carbon mitigation strategies using the EUCalc. Further explanations about each sector module and the references used to calibrate the model can be found in the technical documents available online on the EUCalc website[3]. Some text excerpts shown in this policy brief were obtained from the EUCalc Transition Pathways Explorer pagers prepared by the EUCalc project team.

Is it possible to live in prosperity whilst also mitigating carbon emissions?

The EUCalc demonstrates that it is possible to achieve better living standards for all Europeans without necessarily having to increase greenhouse gas (GHG) emissions. In some scenarios[4] it is possible to significantly reduce GHG emissions whilst also increasing quality of life. It is also possible to achieve a net-zero emissions scenario, which would require a major paradigm shift in all sectors of the European economy, such as transport, manufacturing, agriculture and power, as well as sustainable land use change, food consumption and lifestyle. In contrast, delays in achieving these changes combined with further investments in high-emissions technologies and practices would exacerbate climate change, putting Europe in an irreversible situation to meet its GHG emission targets, as required by European Commission *European Green Deal* (EC, 2019).

In this policy brief, we illustrate how changes in different sectors could affect climate change mitigation, but several other scenarios can be simulated using the EUCalc online. The *EU Reference Scenario* for the year 2050 (European Commission, 2016), available on the EUCalc Transition Pathways Explorer is assumed as a default pathway for comparison (Figure 1). It approximately represents an analogous scenario for the European Union as proposed by Capros et al. (2016).

The subsequent sections show a brief demonstration of some selected scenarios, including answers to some frequently asked questions on carbon mitigation, short descriptions of the main levers used in the EUCalc and illustrative graphs. It is important to mention that these simulations are not GHG emission forecasts, but some scenario exercises, among many other technically possible pathways that can be achieved in the EU[5] by 2050.

The aim here is to demonstrate some ambitious carbon mitigation pathways (sometimes considered to be 'extremely ambitious mitigation efforts' by some experts) towards a net-zero GHG emission. A large number of moderate mitigation pathways can also be demonstrated, but they would leave Europe far from achieving its climate goals, which is not the objective of this policy brief.

In addition, it is important to mention that the EUCalc model provides disaggregated simulation per EU Member State as well.

[3] See more at: http://www.european-calculator.eu/deliverables-disseminations/

[4] The simulations and descriptions here shown are based on the EUCalc Transition Pathways Explorer version available on 15th March 2020, which was subject to previous stakeholders' consultations, and call for evidence. Future updates of the EUCalc may affect the current results.

[5] EU in the brief means the EU28 Member States (including the United Kingdom) as in December 2019, plus Switzerland.

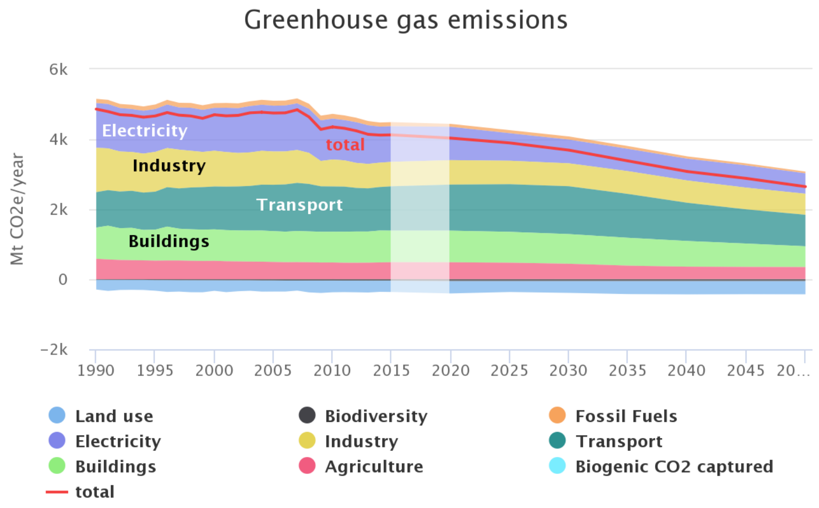


Figure 1: GHG emissions according to the 'EU Reference Scenario' adopted in the EUCalc.

2 Pathways for Changes in Key Behaviours

This section provides a brief demonstration of the *Key behaviours* scenario shown in the list of EUCalc example pathways available in the 'Transition Pathways Explorer' – TPE (the EUCalc model user interface, available at: tool.european-calculator.eu/) and describes the main issues associated with the behavioural impacts on GHG emissions and energy balances.

Does change in people's behaviour really matter?

Every single lifestyle choice matters for carbon mitigation, from changes in the way we travel and heat our homes to changes in the way we eat and consume products. It is a myth that only top-down decisions are important for reducing carbon emissions, bottom-up actions such as the behavioural changes are equally important. **As shown in the EUCalc example pathways, key behavioural changes in the European society could half current GHG emissions** (Figure 2). This scenario portraits the maximum ambition level in the EUCalc model regarding *Key behaviours*, which lead to a more substantial lifestyle change than that considered in the *1.5 LIFE* scenario (LIFE, 2019). In this scenario, emissions related to *Technology and fuels* and to *Land-Food* (as categorised on the EUCalc Transition Pathways Explorer) remain the same as those in the *EU Reference Scenario*.

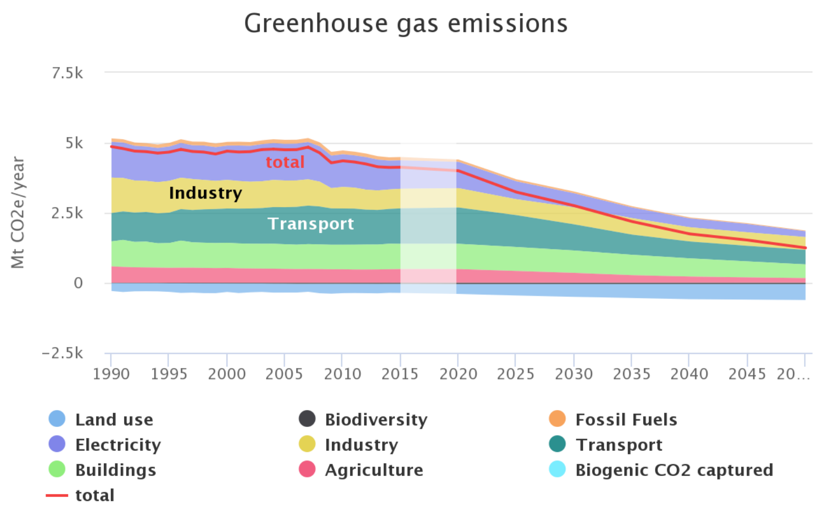


Figure 2: EU GHG emissions reductions from changes in 'Key behaviours', EUCalc.

2.1 Changing how we travel

Behavioural changes regarding the way we travel can significantly affect emissions, for example, by varying the passenger distance, mode of transport, vehicle's occupancy, car own or hire.

How far will we travel in 2050?

An average European travelled about 12,466 km in 2015 and in the scenario above this average would be reduced by 7.1% in 2050. The transport sector represented about 33% of primary energy needs in Europe in 2015 and contributed 25.8% of total EU28 GHG emissions. In this 2050 scenario, passenger distance travelled is conditioned by a 50% reduction of the time spent for travelling to work/study through the full exploitation of tele-work/study, whereas travel time for access to services is cut by 40%, exploiting the full potential of digitalization and automation. The rise in travel time spent for leisure activities is curtailed at 20%. The results for this scenario are summarised in Figure 3.

People at Train Station by Jé Shoots

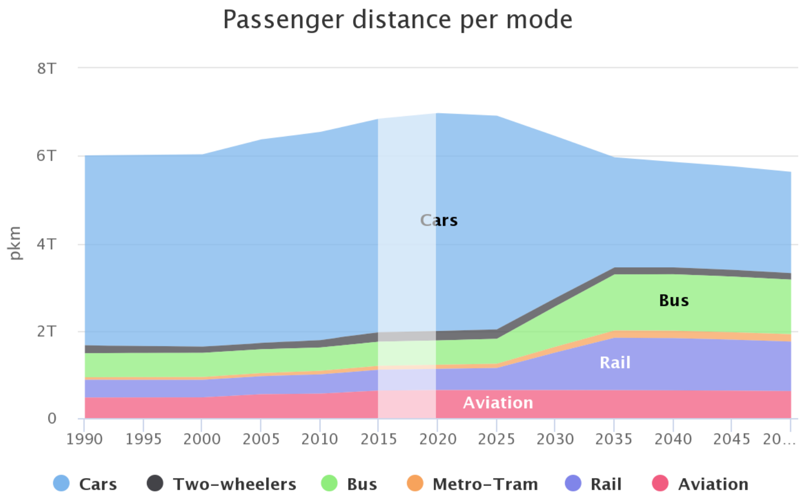


Figure 3: Passenger distance per mode in the EU, under the EUCalc 'Key behaviours' example pathway.

Without the implementation of extensive and sustained mitigation, transport emissions could increase at a faster rate than emissions from the other energy end-use sectors. The transport sector is recognized as particularly difficult to decarbonize, given the investment costs needed to build low-emissions transport systems, considering the slow turnover of stock and infrastructure. **However, a shift towards demand-side solutions for mitigating climate change is now gaining traction.** The demand for passenger travel is controlled by the amount of time a person spends traveling and the average speed of transportation systems. There are three major activities that compose most of the time spent travelling: i) to go to work/study (depending on the age class); ii) for recreation and social activities; and iii) to access services like shopping or medical care. Growth in wealth is usually related to more time spent on travelling for leisure and social activities. **The best opportunities to reduce travel demand, therefore, emerge by lowering the need to travel for work/study purposes** (e.g. via teleworking or home-based work) and to access services (e.g. via automation or tele-medicine).

What transport modes will we use in 2050?

Changes in transport mode, e.g. car or public transport, trains or planes, can significantly affect GHG emissions. In 2015, an average European used a car for 78% of the total distance travelled, whereas in the scenario above cars would account for 54% of the total travelled distance. This change represents an extreme effort to shift people away from the use of private fossil fuelled cars as well as reduce travel demand, requiring a major effort in the development of rail infrastructure and logistics. The mode by which people travel has a big impact on energy use and emissions. See, for example, the passenger energy demand and GHG emission per mode by 2050 under the EUCalc *Key behaviours* pathway (Figure 4 and Figure 5). For passenger travel, the proportion of car use in the mix is particularly important, as fossil-fuel powered cars have high emissions per person compared to public transport. Historically, car use increases as countries develop and cars become more affordable.

Gray Plane Wing Under White Clouds by Josh Sorenson

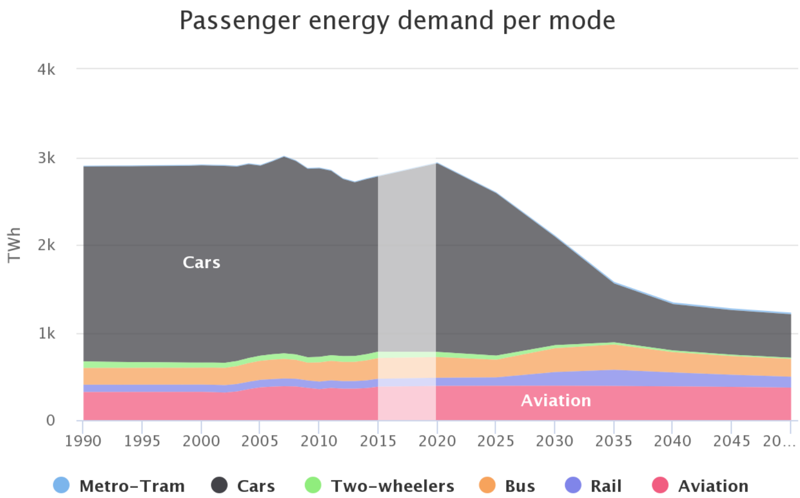


Figure 4: Passenger energy demand per transport mode in the EU, under the EUCalc 'Key behaviours' example pathway.

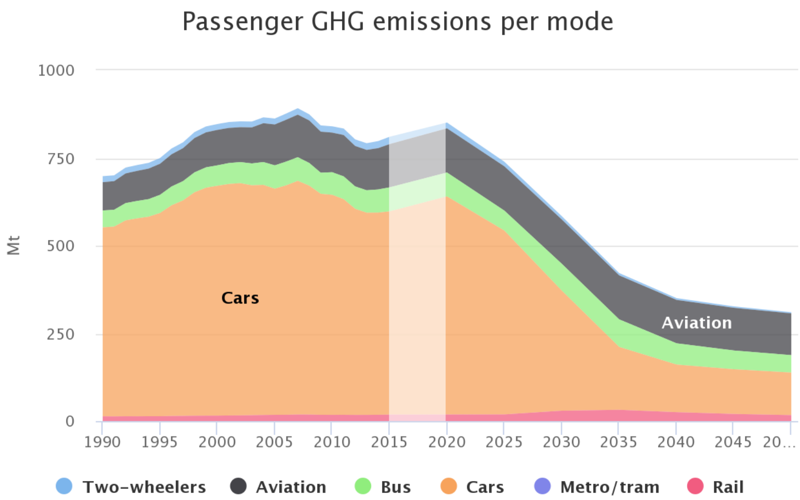


Figure 5: Passenger GHG emission per transport mode in the EU, under the EUCalc 'Key behaviours' example pathway.

Although growth in car ownership has long been associated with increasing prosperity, a shift to public transport, walking or cycling does not necessarily mean less convenience for passengers and a lower quality of life. **If cities are carefully planned with integrated transport systems, journeys may be quicker by public transport.** Quality of life can be improved by spending less time stuck on congested roads and by being less exposed to air pollution. Figure 6 shows a significant decline in mortality rates due to air pollution under the EUCalc *Key behaviours* scenario. However, the development of public transport infrastructure and urban planning usually requires significant public investment, whereas the growth of car use involves the spending of mostly private money. **This means that considerable political and civic will and effort must be made to produce the significant shift in transport mode for an ambitious carbon mitigation pathway.**

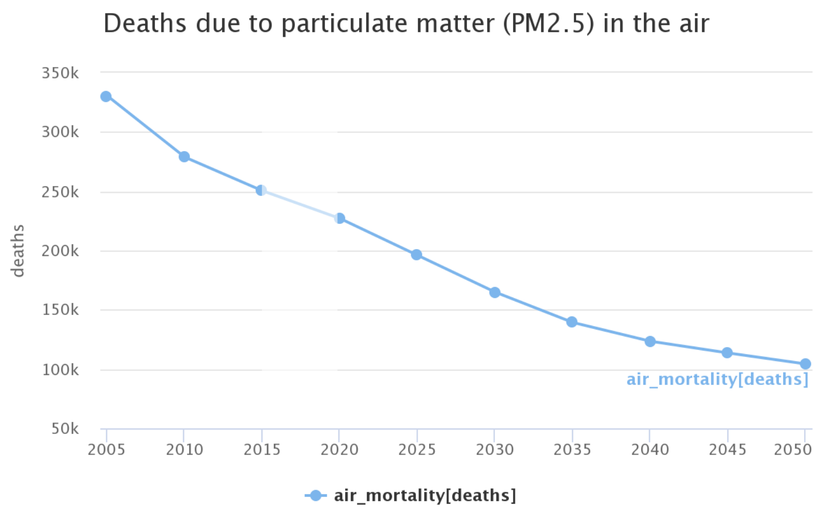


Figure 6: Number of deaths from air pollution in the EU ($PM_{2.5}$ index), under the EUCalc 'Key behaviours' example pathway.

How will the occupancy for passenger cars be in 2050?

In 2015, a car in Europe carried about 1.6 persons on average and this number would increase to 2.6 persons per car by 2050 (i.e. 63% increase) in the *Key behaviours* example pathway, and the average occupancy for other transport would be higher too. **This scenario assumes that regulatory constraints, costs, and smarter digital applications to coordinate our car demand and use would make car-pooling more attractive.** While most cars have more than two seats, their occupancy tends to be less than two people. Similarly, many freight transport vehicles are not loaded to their full capacity. Historically, freight transport load factors have increased due to improved logistics and distribution systems. In contrast, car occupancy has decreased. An explanation might be the increasing global wealth allowing for more car ownership as well as the greater diversity of activities and destinations available to people. People who may have originally travelled as a group or used public transport, now go with their own cars. **However, as awareness grows and congestion and parking costs increase in some urban areas, the use of car-pooling and car sharing may become a more appealing prospect in the future.**

Will car-pooling and sharing increase the distance undertaken by each vehicle in 2050?

There are several ways to increase car utilization rate such as the transition from individual car ownership to car sharing models. Various factors influence the adoption of car sharing in the population, such as: localization/proximity of shared vehicles; vehicle availability; reservation system; costs of the services; and savings compared to owned vehicle. In the car occupancy scenario described above, cars would run 900% more km per year in 2050 than in 2015. **As a result, this will mean a radical behavioural change in terms of car ownership and the intensification of car sharing, car-pooling and automation, in order to achieve the more than 900% km cars run per year target in 2050.**

2.2 Changing our homes

Changes in the way we live in our residences can also impact GHG emissions. Some key variables can measure these impacts, namely: living space per person; the percentage of cooled living space; space cooling and heating; appliances owned; appliance use.

How much living space will we need in 2050?

An average European had 46.1 m^2 of residential floor to live in 2015. In the same EUCalc *Key behaviours* scenario, this average living space would be 37.4 m^2 per person in 2050 (Figure 7) i.e. 19% lower than in 2015, directly affecting also the energy demand (Figure 8). The current value may sound small, but it is worth noting this is an average figure and it includes the fact that many people live in a same house, for example, a family house or shared house and, therefore, the total floor area is divided by the number of residents. Moreover, this simulation reflects a transformational level targeting sustainability. Rao and Min (2018), for example, suggest the value of 37 m^2 per person (that of China's average home size in urban areas and like the EU28 in the year 2000) as the benchmark for decent living in affluent countries. As an extreme comparison, in South Korea, an affluent country with living standards at par with rich European countries, the minimum standard for living space is 12 m^2 per person (Rao and Min 2018), showing that in some geographic contexts a very low floor-space per capita is possible, even when the country is affluent.

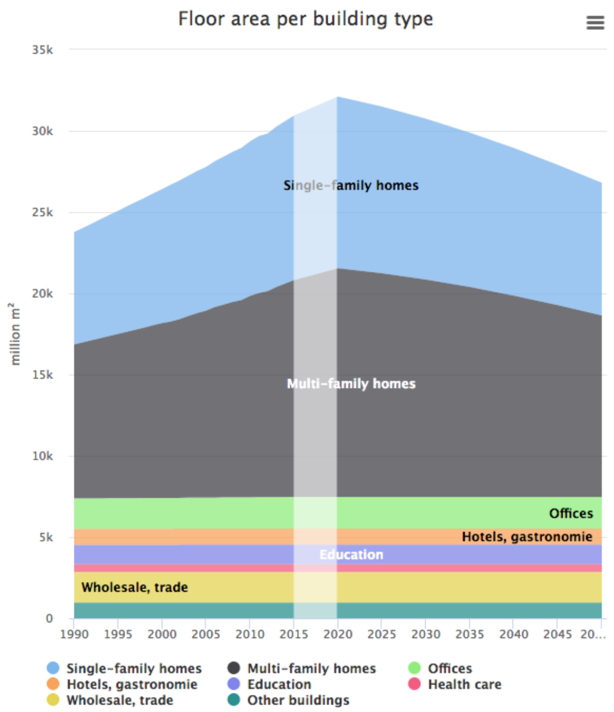


Figure 7: Floor are per building type in the EU, under the EUCalc 'Key behaviours' example pathway.

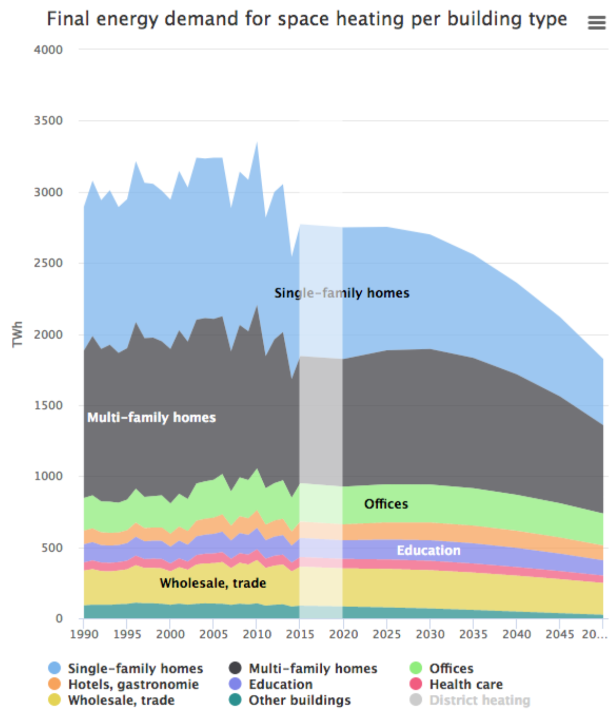


Figure 8: Energy demand per building type in the EU, under the EUCalc 'Key behaviours' example pathway.

The amount of residential floor space is a very common reference value to determine the energy use intensity of buildings and the amount of raw materials needed for its construction. Average per-capita residential floor area across the EU28 Member states increased from 36 to 45.5 m^2 between the years 2000 and 2014. **A decrease in the intensity** (that is, less floor space per person) **would therefore yield reductions on the total amount of energy requirements for the heating of buildings**[6]. Given that 50% of annual energy consumption in buildings is associated with space heating and cooling, residential floor space per person becomes an important factor of GHG emissions. For the EUCalc *Key behaviours* example pathway above, the GHG emissions from the different building types are shown in Figure 9.

[6] See more at: https://ec.europa.eu/energy/sites/ener/files/DG_Energy_Infographic_heatingandcolling2016.jpg

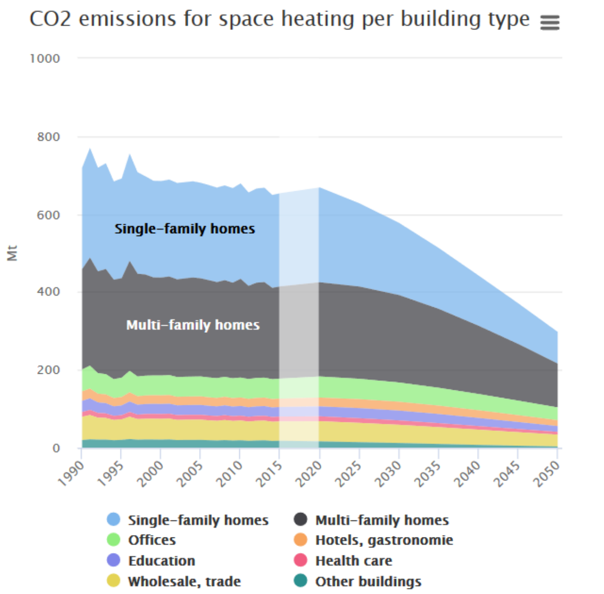


Figure 9: EU GHG emissions per building type under the EUCalc 'Key behaviours' example pathway.

What percentage of living space will be cooled in 2050?

In the simulation above for a strong behavioural change, the current percentage of residential living space with cooling system (about 10% in 2015) would remain approximately the same (10.6% in 2050). **The small increase is assumed in order to safeguard the growing fraction of vulnerable population to heat stress, namely the elderly.** In contrast, current trends show that this value tends to increase more substantially, especially if the average mean surface temperature in Europe keeps rising in the coming decades. In 2015, the amount of residential living space area cooled varied between values of more than 50% in Malta and Cyprus to less than 0.5% in countries such as Finland or Germany. **The variation reflects the main driver for requiring cooling (high outside temperatures) although it is also noted that income levels also play a role.**

For large parts of Europe, increases in cooling energy demand due to global warming is said to outweigh the expected reductions in energy for heating. Depending on the generation mix, in some countries, the net effect on GHG emissions may be an increase even where overall demand for delivered energy is reduced. Given that a certain amount of global warming between today and 2050 is unavoidable (given the large amount of emissions already in the atmosphere), **the EUCalc model assumes in any scenario that an increase of cooled area in residential buildings would be required**.

To what temperature will we cool or heat our houses in the summer or winter in 2050?

The comfort room temperature in Europe is about 20ºC (Ballester et al., 2011), but this value may change in the coming decades. The simulation conducted here assumes a thermal-comfort temperature (Figure 10, Figure 11), but some temperature variations are observed for other scenarios. Research suggests that **energy savings of up to 15% are possible for each degree of temperature increase or decrease in buildings**. Each country has its so called "comfort temperature" based on variables such as weather, age, structure and population wealth. Current comfort temperatures range from 14°C in central Europe to 25°C in Southern Spain, and they are significantly higher than annual mean temperatures.

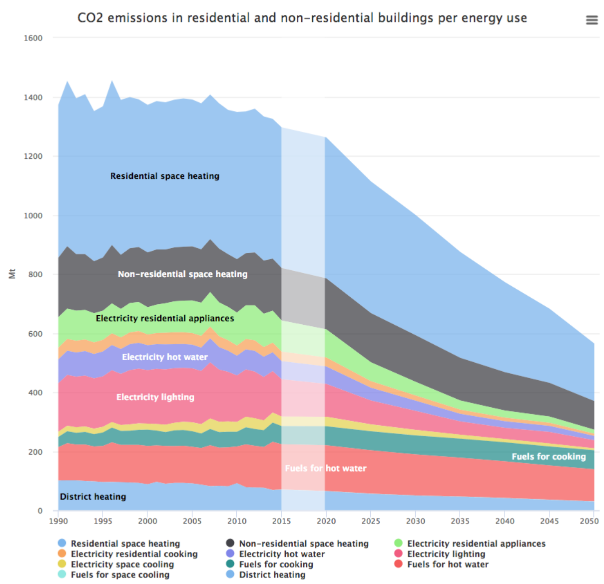


Figure 10: EU GHG emissions per use in buildings under the EUCalc 'Key behaviours' example pathway.

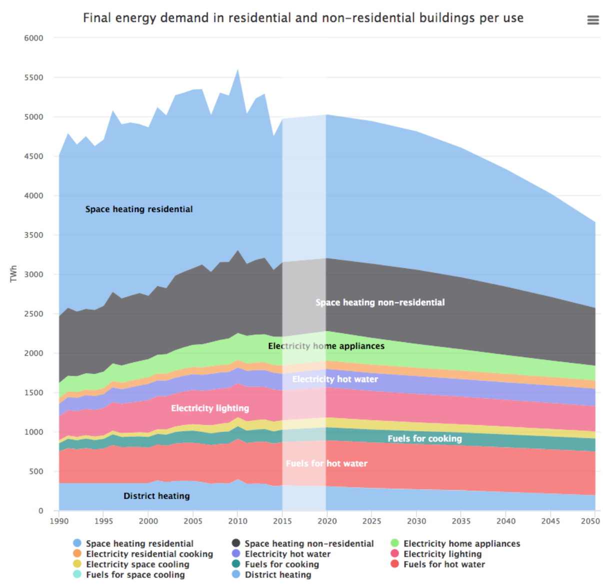


Figure 11: EU final energy demand per use in buildings under the EUCalc 'Key behaviours' example pathway.

How many appliances will we have in our houses?

An average European has several appliances at home, but some appliances can consume much more energy than others. For example, in 2015, an average European household had 1.7 computers and 0.9 washing machines. Although these values tend to keep increasing, **in our simulation an average household would have 1.3 computers and 0.8 washing machine by 2050, as an extreme effort to reduce GHG emissions**. This simulation also assumes countries converge to appliance ownership closer to that of countries with middle income (typically between €20,000 and €30,000/capita in 2014). This is a level of income that would eliminate the monetary barrier of buying an appliance while containing the prospect of households buying more appliances than necessary. At this level, dishwasher ownership would converge towards 0.5 per household (the same as Italy in 2014); computer ownership would be at 1 per household (the same as Spain in 2014); TV's would be at 1 per household (similar to the level of Slovenia in 2014). In the case of washing machines, ownership would converge towards 0.8 per household in 2014, reflecting the levels found in Switzerland.

Appliances use more than a third of the global energy consumed in buildings. Globally, the growing share of appliances in electricity demand has been driven by the growth in large appliances (increasing 50% since 1990); lighting (growing on average 2% annually since 2005); and networked devices and consumer electronics (increasing 3.5% annually since 2010) (IEA, 2017). Intlekofer et al. (2010) showed that, **on average, up to 30% of energy could effectively be saved by leasing** dishwashers, washing machines and refrigerators, whereas the **potential for energy savings for renting out computers was between 20-30%**.

How many hours will we spent in front of a screen in 2050?

An average European spent 2.3 hours in front of a TV and 1.2 hours in front of a computer per day in 2015. The use of computer at home may increase over time. However, in our simulation for **the *Key behaviours* example pathway, it is assumed that the time spent in front of TVs and computer would be approximately 1 hour for each of them, per person a day, in 2050**, which is in line with the health recommendations of the World Health Organization (WHO, 2019). For the use of dishwashers, dryers and washing machines, this pathway assumes the operation time found in Scandinavian countries and taken from the Pan-European Consumer Survey (AISE, 2014), namely 0.7, 0.3 and 0.3 hour per day, would be further reduced by 20% as an average for the European Union. Between 2002 and 2010, TV viewing decreased slightly in most of European countries (exceptions are Greece and The Netherlands). The decrease was more than offset by a sharp increase in computer use which was consistent across all countries (Bucksch et al., 2016).

2.3 Changing how we eat

Dietary patterns have significant variations across European nations. The number of calories consumed per person and the type of diet (e.g. high-meat consumption vs. vegetarian diet) can significantly affect GHG emissions, because they are linked to agricultural and livestock production, land use change, processing and storage and wastes.

How will our calorie consumption evolve in 2050?

An average European required 2,474 kcal/person.day in 2015. This value may keep increasing, whilst also affecting higher incidences of obesity in Europe. **However, in our simulation, we assumed that this figure would be 2,386 kcal/person.day in 2050** (3.7% decrease compared to 2015), as an exercise for an extreme change in diet. Energy requirements are reduced reflecting lifestyle changes that favour **eating just the necessary number of calories to guarantee that the current obesity prevalence in Europe drops by 50%**.

Assorted variety of Foods on Plates on Dining Table by Daria Shevtsova

It is worth noting that these calorific values represent food intake and not the total amount of calories available in terms of food supply per capita (which includes wastes). Average calories available in Europe stood at 3,316 kcal/person.day in 2013, an increase from 3,281 kcal/person.day in the year 1990. The distribution of calorie availability ranges between countries with typical calorie availability of 3,200 Kcal (e.g. Sweden) to countries with 3,600 kcal/person.day (e.g. Ireland). **Should the efficiency of agricultural systems stagnate in the delivery of more food per tonne of CO_2, a reduction** (particularly in the rich world) **of food demand is a viable option to reduce GHG emissions.** For example, studies have shown that eating less food in general could lower GHG emissions by reducing food demand, which could be lowered by up to 20% in some countries (Vieux et al., 2012).

What type of diet will we have on average in 2050?

Changes in dietary pattern is an issue of high controversy. Whilst some people advocate the consumption of meat products, others defend that a vegetarian diet would be the best choice for reducing GHG emissions, whilst also reducing pressure over land resources. In 2015, the meat consumption for an average European was 343 kcal/person/day. In our extreme simulation, this value would be 92 kcal/person/day, i.e. 73% decrease compared to 2015, and in line with a flexitarian diet. **This simulation also assumes the widespread adoption of a flexitarian diet as proposed in Sringmann et al. (2018), which means that meat consumption would be kept at 38g per day with 13g per day of red meat.** Sugars and sweeteners would be kept at below 5% of calorie intake, whereas fruits and vegetables consumption would account to over 600g/day.

Bowl of Vegetable Salad by Buenosia Carol

Consequently, a minor reduction in total calories per capita associated with a substantial reduction in meat consumption (with equivalent calories compensated with plant-based food) would change the pattern of crop consumption over time, as shown in Figure 12 under the EUCalc *Key behaviours* example pathway.

With a reduced meat demand, for example, less feedstuffs would be required for livestock production. This specific scenario also assumes that crop-based bioenergy would decline over time, although more bioenergy could be produced from biomass residues and wastes. More favourable scenarios to bioenergy can also be demonstrated, as further discussed in section 4.1.

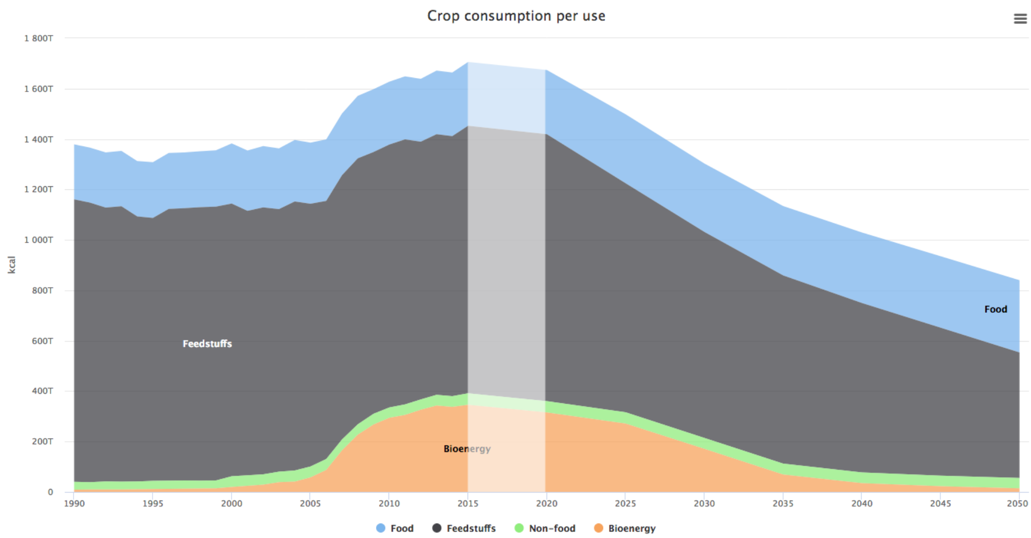


Figure 12: Crop consumption per use in the EU, under the EUCalc 'Key behaviours' example pathway.

The total share of animal-based calories is estimated to rise globally with only a moderate increase for high-income countries. For some countries, reductions in meat consumption are possible even with increasing income (Bodirsky et al., 2015). **A shift in consumption towards more animal-based products are expected to lead to an increase in GHG emissions.** Hence, dietary shifts have been proposed as an effective way of reducing associated GHG emissions (Springmann et al., 2018).

2.4 Changing how we consume different products

The consumption of goods has GHG emissions associated with them. For example, the use of paper for packaging, household appliance end-of-life (retirement timing), freight distance, and food waste in households. Therefore, behavioural changes towards a sustainable consumption can significantly contribute to mitigate carbon emissions.

How will packaging use change in 2050?

In 2015, Europe used approximately 30 kg of plastic packaging per person a year, and this value tends to keep increasing by 2050, unless significant changes are made. **In the simulation for key behavioural changes done using the EUCalc, it was assumed that the use of plastic packaging would be about 17.6 kg/person/year in 2050 (59% decrease compared to 2015)**. In this extreme scenario, the reduction in demand for paper was extended to 56% by 2050, reflecting the feasibility expressed in Calloway (2003) and Moberg et al. (2010), whereas the use of sanitary paper would be stagnated. The technical feasibility of reducing plastic and aluminium packaging consumption by 10% described in Moran et al. (2018) has been applied for this scenario, as well as a growth of 70% in glass packaging in order to compensate the reduction in plastic and aluminium materials.

In 2015 the global demand of paper for print declined and the fall in demand for this product in Europe over the past five years has been more pronounced than even the most pessimistic forecasts. The use of paper packaging, on the other hand, is growing in Europe along with the use of tissue paper, and the use of pulp for hygiene products. The demand for plastic products in 2017 totalled 52.1 Mt (Plastics Europe, 2017), about 15% of the global production. Among the several uses plastic can have in Europe, the main use is for packaging (approximately 40% of total production) followed by building and construction (about 20%) and finally the demand from the automotive industry (approximately 10%).

How long will household appliances be kept before they are disposed of?

The lifetime of household appliances may substantially vary and change over time according to the type of product. The residence time of computers, for example, has decrease by around 10% from 2000 and 2010.

In the 2050 scenario simulation done for EUCalc *Key behaviours* pathway, it was assumed that **computers, TVs, and phones would be replaced at 130% of their lifetime**, reflecting the feasibility shown in Moran et al. (2018) study. **For washing machines, dishwashers, dryers, fridges and freezers, the replacement would take place at 110% of the product lifetime** in order to avoid the rebound effects of potentially old appliances with low energy standards.

In the Netherlands, a study of flows in electrical and electronic equipment (Huisman et al., 2012), concluded that basically all appliances investigated showed decreasing residence times for equipment put in the market in 2000 versus those that were introduced in 2010. The residence time of IT equipment reduced by 10% while washing machines and dishwashers by 7%. Traditionally, much more attention has been placed on the amount of energy used by a product rather than the amount of energy it took to produce it. But not all appliances are created equal. White appliances, including refrigerators, washing machines and dishwashers, require a significant amount of energy to produce but their overall (full lifecycle) energy expenditure takes place during operation. **Manufacturing of white appliances accounts for only up to 12% of the total lifetime energy use** (Gonzalez et al., 2012). On the other hand, products with shorter useful lives as well as those with semiconductor manufacturing (e.g. electronics) tend to have much higher relative embedded energy and GHG emissions contribution compared to products with motors, pumps, or compressors (Kirchain, 2011). Products such as computers have a higher proportion of their overall energy use tied to their production in the range of 40 to 80% of their total lifecycle energy use. **The more we use an appliance above and beyond its expected lifetime, the greater the potential for saving its lifetime energy use**.

How much food will we waste in our households in 2050?

Reducing food wastes is one of the key measures towards reducing GHG emissions, given that several natural resources (land, soil, water, energy) are required to produce them. Food waste at consumer level in Europe was approximately 515 kcal/person/day on average in 2015. **In the *Key behaviours* simulation, food wastes represent 130 kcal/person/day in 2050, i.e. a 75% reduction compared to 2015.** Food waste for the whole EU28 was estimated at 88 million tonnes in 2012 (Stenmarck et al., 2016). This equates to 173 kg of food waste per person. The total amount of food produced in the EU for 2011 was estimated at 865 kg/person, this would mean around 20% waste of the total food produced (in weight terms). **Therefore, an overall reduction in daily calories of food wasted, with all other variables kept constant, would lead to a reduction in carbon emissions from the agricultural sector**.

What would the freight transport demand be in 2050?

Total freight demand in Europe is currently about 3781 billion tonnes-km and in our simulation for the *Key behaviours* example pathway, this total would reduce by 22% in 2050 i.e. 2756 billion tonnes-km. Historically, the demand for freight transport is strongly related to the economy, in terms of Gross Domestic Product (GDP). A higher GDP implies a higher level of production and consumption, which in turn translates into a higher demand for transporting the produced goods. **Low-carbon scenarios that lean towards a local circular economy, based on sharing and where mobility is seen as service, could however decouple freight activity from GDP.** In 2015, the energy demand for freight only represented a third of the energy consumption related to passenger transport in Europe. The proportion is similar for GHG emissions as well. However, as freight transportation modes are harder to decarbonise than passenger transportation modes (e.g. trucks/lorries vs. cars), the share of freight related GHG emissions in total transport GHG emissions is likely to increase.

Photo of Cargo Ship on Body of Water. Source: Pixabay

3 Pathways for Changes in Technology & Fuels

In this section we show how changes in *Technology and fuels* (as categorised on the EUCalc Transition Pathways Explorer) can affect GHG emissions in Europe, including a brief simulation and descriptions related to the *Technology and fuels* example pathway available on the EUCalc Transition Pathways Explorer.

Is it worth changing our technologies and fuels for carbon mitigation?

The EUCalc shows that changing and improving technology and fuels can significantly reduce GHG emissions (Figure 13). The *Technology and fuels* example pathway portraits the maximum ambition level in the EUCalc for *Technology and fuels*, whilst *Key behaviours* and *Land-Food* evolve as those in the *EU Reference Scenario*. Thus, technology innovation can play a major role in climate change mitigation, including taking further carbon mitigation efforts in all other sectors of the economy, such as transport, buildings, manufacturing and power.

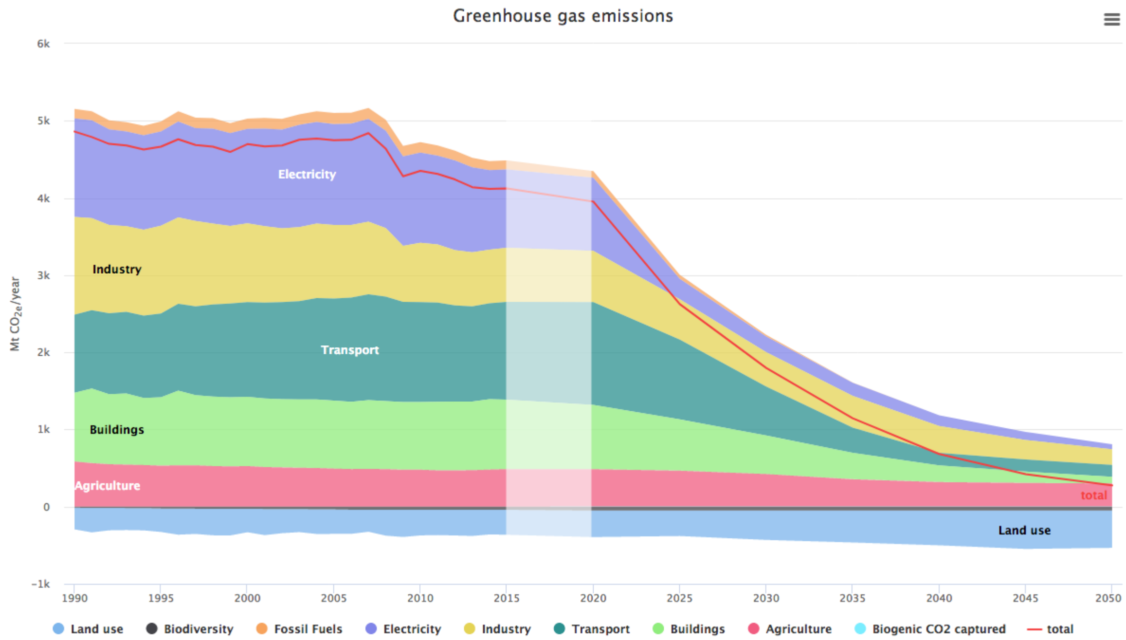


Figure 13: EU GHG emissions reductions from changes in 'Technology and fuels', EUCalc.

3.1 Improving our transport system

There are several ways to mitigate GHG emissions in the transport sector, for example, improving freight and passenger efficiency and technology, freight mode and utilization rate and fuel mix. While sections 2.1 and 2.4 already discussed behavioural changes regarding the use of transport, this section 3.1 focuses on technology and fuels associated with the transport sector.

How will the efficiency of new passenger vehicles evolve by 2050?

In our simulation for an ambitious mitigation effort in *Technology and fuels*, the car energy consumption (MJ/tkm) would decrease by 50%, bus energy consumption by 30%, rail energy consumption by 45%, and aviation energy consumption by 30%. In recent years, there has been a strong focus on improving the fuel efficiency of cars. The fleet consumption of Daimler, for example, fell by about 50% between 1990 and 2012 to around 6.5 litres per 100 km. This was achieved by technology improvements (cylinder capacity and turbo charging) and regulatory efforts, such as lower limits for fleet efficiencies. Given the significant progress achieved in the past few years it is difficult to envisage major improvements in the near future for fossil-fuel-powered car engines. However, car efficiency could be improved by decreasing the average car weight so that less fuel is needed. **Policy approaches might be able to increase average transport efficiency by setting more severe speed limits for cars which would run more efficiently at lower speeds**.

The efficiency of planes has also improved over the last decades. The jumbo jet A380 is 12% more efficient than a Boeing 747, **but it is difficult to predict if significant improvements can be expected in the near future**. Replacing fossil fuel with alternative fuel sources (e.g. hydrogen) might not help reduce the climate impact of flying as water vapour acts as a strong greenhouse gas. When directly emitted in the stratosphere, water vapour can persist for months and years and might also degrade the ozone layer. Significant research efforts are going into low-emission vehicles, meaning that efficiency improvements are also likely for hydrogen-powered and electric vehicles.

There are several ways to enhance vehicle efficiency, such as improving the engine or aerodynamic performance of vehicles, using lighter materials to reduce the ratio of weight per person, or changes in driving behaviour (for example, braking less or travelling at lower speeds). Regarding passenger transport, public transport (electric trains, trams and buses) is about 5 to 10 times more energy-efficient than other forms of transport (e.g. cars and planes). For freight transport, in 2011 light-duty vehicles had an efficiency of 10 litres gasoline equivalent (lge) per 100 km and heavy-duty vehicle efficiency was 32 lge per 100 km. The average global rate of improvement is of 1-2% per year. International shipping is more efficient in fossil fuel use and is also compatible with biofuels, whereas nuclear reactor driven ships have cargo transport cost as low as 0.14 kWh per tonne and km and can travel 500,000 km without refuelling.

What will be the uptake of zero-emission vehicles (electric or hydrogen) and low emission vehicles (hybrid or natural gas) in 2050?

White and Orange Nozzle by Mike

Only 0.4% of newly sold passenger cars were electric vehicles in 2011, whereas 99% of passenger cars were powered by fossil fuel based on internal combustion engines. Transport is one of the major contributors to global GHG emissions and it is still heavily reliant on fossil fuels. However, the share of electric vehicles has been increasing over time. **In our simulation for an extreme scenario in *Technology and fuels*, zero-emission vehicles (battery electric vehicles, and fuel-cell electric vehicles) would represent 100% of new sales in the European Union**. This would directly affect the share of existing passenger car fleet according to different technology types over time, as shown in Figure 14.

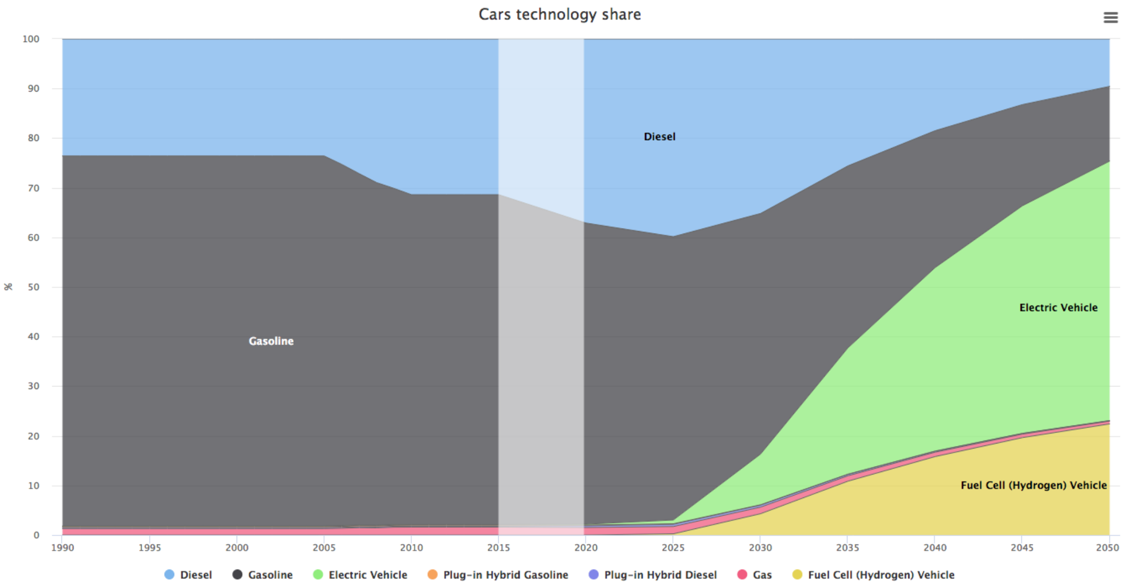


Figure 14: Car technology share in the EU, under the EUCalc 'Technology and fuels' example pathway.

Therefore, **a switch to low emission transportation could reduce GHG emissions substantially**. As the lifetime of an average passenger vehicle in Europe is around a decade, low carbon vehicles could be introduced over relatively short periods. Electric vehicles and some types of hydrogen fuel-cell vehicles have existed for many years, but their actual uptake has been small. Recently, some countries have introduced significant incentive systems to support the uptake of low emission vehicles. In 2019, Norway, for example, had 15% share for zero- and low-emission vehicles as part of its car fleet. **Car manufacturers are investing in low-emission vehicles with a focus on electric and hydrogen**. After the big success of hybrid engines (combining a combustion engine and an electric motor for energy recovery), Toyota for example moved on to hydrogen engines and launched its first purely hydrogen-powered car in 2015. On the forefront of electric vehicles are companies such as Tesla and BMW. The take up of electric and hydrogen vehicles will ultimately depend on technological advancement and whether they are seen as affordable and desirable by consumers, public transport providers and freight companies.

On the other hand, the impact of technology improvements on the GHG emissions will depend on how the electricity or hydrogen used to power these vehicles is generated (this is considered in the EUCalc), as well as on the level of transport demand predicted by 2050. In spite of the many proponents of low emission vehicles citing positive effects such as less air pollution in cities as well as quieter streets, the uptake of low emission vehicles has so far been hampered by high prices, range anxiety, slow charging, as well as limited infrastructure available to charge vehicles. Recently, manufacturers and energy suppliers have focused on expanding charging infrastructure for low emission vehicles. To enhance take up, a group of leading car manufacturers have recently agreed on a fast charging standard allowing battery charging to 80% within half an hour – this might help to implement a working charging network.

How efficient freight vehicles will be in 2050?

Energy consumption in freight (load transport) is an important area to tackle climate change, given that it is highly dependent on fossil fuels, especially diesel. **In our simulation for an ambitious change in the energy efficiency, energy consumption per distance (MJ/tkm) would decrease by 50% for trucks (lorries), 40% for rails, 22% for aviation, and 40% for shipping**. In 2011, light-duty vehicles for freight transport had an approximate efficiency of 10 litres gasoline equivalent (lge) per 100 km and heavy-duty vehicle efficiency was 32 lge per 100 km. The average global rate of improvement is about 1% to 2% a year. International shipping is more efficient in fossil fuel use and is compatible with biofuels as well. More recently, in 2018, the European Commission drafted the first ever truck CO_2 emission standards (European Commission, 2018) that plans to reduce truck-related emissions by improving efficiency, and to increase the share of zero-emission vehicles in the truck fleet.

What will be the share of low- and zero-emission vehicles in the total sales of new freight vehicles in 2050?

In freight transportation, low carbon emission vehicles, such as gas (using internal combustion engine – ICE) and plug-in hybrid vehicle (PHEV), and zero carbon emission vehicles, such as battery-electric vehicle (BEV) and fuel-cell electric vehicles (FCEV), can play a major role in reducing GHG emission in the European Union, including road, rail, sea and air transport. By 2050, these technologies could represent as low as 10% of the new truck sales, for example, but in the 'Technology and Fuel' pathway this share would reach 100% of the new truck sales.

Decarbonising the freight sector is more challenging than passenger transport, given that low- and zero-emission alternatives to fossil-fuel engines are currently harder to implement. For example, it is currently hard to have fully electric trucks powered with batteries due to the significant amount of batteries needed and their weight. The impact from the use of electricity in freight transport on GHG emissions will also depend on how the electricity or hydrogen used to power these vehicles is generated, which is also considered in EUCalc.

How will the freight transport demand be split between the different modes in 2050?

The mode by which freight travels has a big impact on energy use and GHG emissions. The proportion of trucks in the mix is particularly important, as trucks have high emissions per tonne-km compared to rail or sea. The current use of trucks is approximately 35% of the total freight transport, but this share tends to increase overtime if no further mitigation effort is implemented. In contrast, rail has a much lower emissions factor per tonne-km, but will require a large infrastructure investment across Europe, if it is to maintain its current share. **In the *Technology and fuels* example pathway, the share of different modes for freight transport in 2050 would be approximately 35% for trucks, 24% for rail, 7% for inland shipping, 34% for maritime shipping and 0.1% for aviation**. This change would directly affect the energy demand for freight transportation (Figure 15).

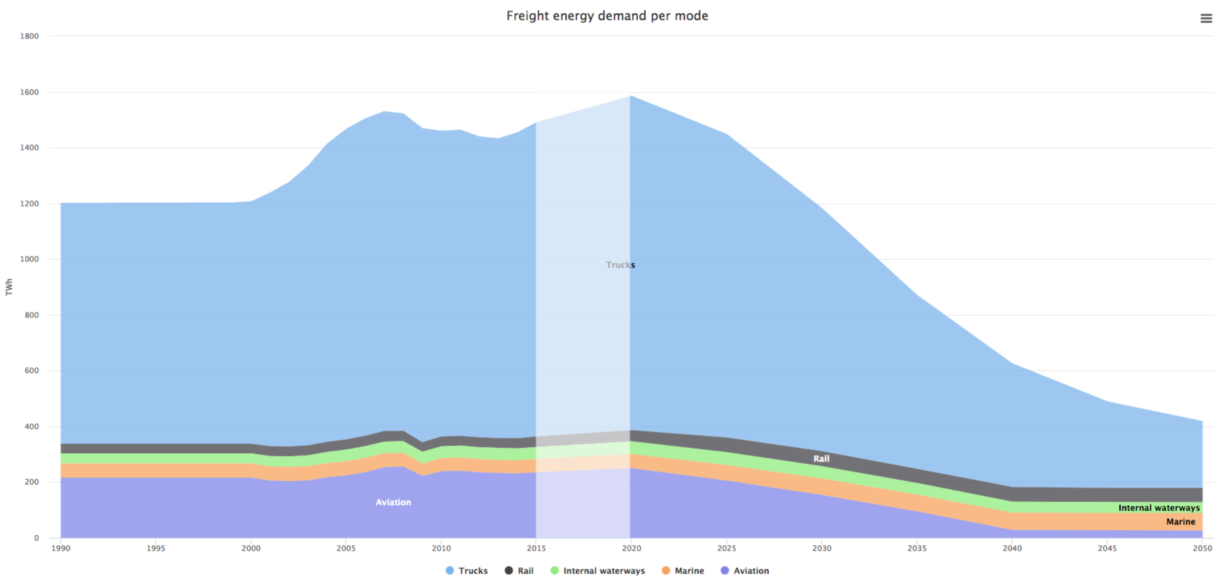


Figure 15: Freight energy demand per transport mode in the EU, under the EUCalc 'Technology and fuels' example pathway.

How will the utilization rate of trucks be in 2050?

It is not only important to increase the efficiency of the vehicle's engines or to change the transport mode, but also to maximise the use of the available vehicles. As already mentioned, trucks have a major impact on GHG emissions in the freight sector. In our simulations for an ambitious change in this area (based on the *Technology and fuels* example pathway) in 2050, trucks would have 15% higher load and would run 10% more distance (km) per year, compared to 2015. Historically, freight transport load factors have increased due to improved logistics and distribution systems. As for the passenger transport, automation is expected to have a strong impact on the utilization of trucks. Technological advancements have also helped increase freight load, for example through applications of software, that ensure a freight vehicle is appropriately loaded as possible whilst preparing for its journey.

How much of the fuel demand in the transport sector (passenger and freight combined) will be met by biofuels and e-fuels in 2050?

Fuel mix can substantially affect GHG emissions too. In the EUCalc, given the evolution of different motorization technologies (e.g. uptake of electric and fuel cell vehicles), the fuel demand may vary accordingly in reference to different mixes. Every conventional fuel (e.g. diesel, gas, gasoline, kerosene, marine fuel oil) used for internal combustion engines (ICE) and hybrid vehicles (PHEV) can be replaced by its equivalent biofuel (produced from biomass) or e-fuel (synthetic fuels, produced from hydrogen and carbon monoxide). In 2015, 4.8% of the fuel demand in the transport sector was covered by biofuels in the European Union. Scenarios for fuel mix in the transport sector are difficult to predict, due to the several uncertainties involved, such as technology development, land use, and regulatory framework. The EUCalc offers a range of different mix options. **For a very ambitious scenario, as represented in the *Technology and fuels* pathway, it is projected that biofuels would represent 100% of total road fuels in 2050, and 66% of marine and aviation fuels (and no e-fuels)**.

Sustainable biofuels can help decrease the carbon footprint of transport. **On the other hand, a potential large-scale expansion of biofuels production in Europe may (or may not) compete with other land uses. Thus, it is important to ensure that this expansion would occur in a sustainable manner, in synergy with food production and forest conservation**. E-fuels are also an interesting alternative. Synthetic fuels can be generated exclusively with renewable energy and are not technically different from their conventional counterparts (they can even be used in classic cars). However, producing synthetic fuels is currently a costly and little efficient process, as production requires a lot of energy.

How much costs would be required for the transport sector in 2050?

Figure 16 and Figure 17 show an approximate cost projection for transport capital expenditure per mode and energy cost, according to the EUCalc *Technology and fuels* example pathway by 2050. In terms of capital expenditures per transport mode, light-duty vehicles (LDVs) would remain as the dominant mode. The fuel costs would significantly decline due to a strong electrification of the transport sector in this specific simulation.

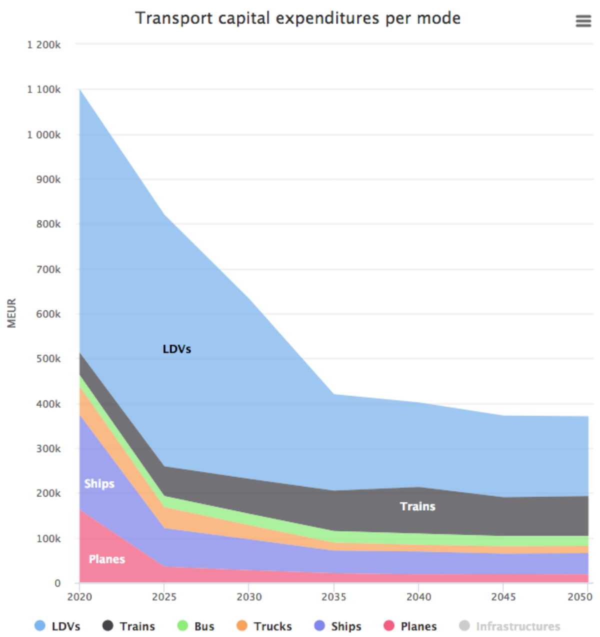


Figure 16: Capital expenditures per transport mode in the EU transport sector, under the EUCalc 'Technology and fuels' example pathway.

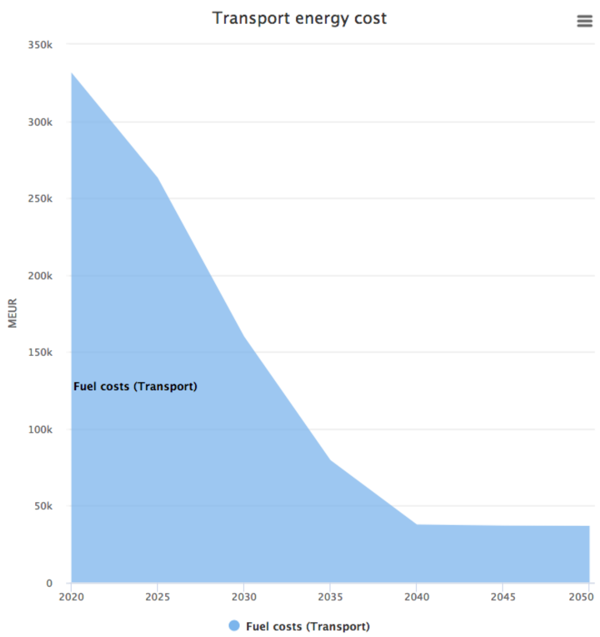


Figure 17: Energy cost in the EU transport sector, under the EUCalc 'Technology and fuels' example pathway.

3.2 Changing our buildings

Buildings are an important sector for climate change mitigation. Two key areas that requires special attention are the energy consumption for thermal comfort (e.g. heating, cooling) and for home appliances.

How efficient will our buildings be in 2050?

The current energy needed for heating (delivery energy) is 180 kWh/m^2 on average for Northern and Western Europe, whereas for Southern and Eastern Europe this consumption is about 100 kWh/m^2. Therefore, the building envelope, including aspects related to insulation and better management of solar radiation and ventilation, is key to reduce energy consumption. **In our simulations for the *Technology and fuels* example pathway, in 2050, all current building stock would be renovated or newly constructed and consume mostly 60% less energy than before**. The average renovation rate in Europe is currently about 1% per year, which would leave large parts of the buildings stock unchanged by 2050. In this projected pathway, the renovation rate in the EUCalc would be approximately 3% in 2050. This assumes that 30% of the renovations would be medium (-40% energy demand) and 70% would be deep (-60% energy demand), and that 30% of the new constructions would have a medium energy efficiency level and 70% would be highly efficient, whereas the demolition rate would be about 1% per year.

Men on Brown Scaffolding by Daria Sannikova

Currently, heating and cooling accounts for around 30% of all buildings' energy demand. The amount of energy required for heating or cooling buildings can be reduced significantly by improving the insulation of external walls, floors, roofs, ceilings, windows and doors. As a result, less heat energy will escape from the inside of the buildings in cold weather, whilst less heat from outside can get in when cooling is on during hot seasons. **The annual energy requirement of a building is affected by both internal and external conditions and the nature of the building's response to these changes.** Similarly, heat transmission, controlled or uncontrolled ventilation, internal and solar heat gains has an impact on the energy needs of buildings. All these parameters set out the energy performance of the building envelope and are reflected in the EUCalc, which includes not only changes in wall/roof insulation, but also alterations in the quality of windows and doors as well as glass type. **Thus, a change in the energy performance of the building envelope can be achieved through renovation that improves building components**.

How much district heating will we use in 2050?

In the simulation for a very ambitious mitigation effort, as shown in the EUCalc *Technology and fuels* pathway, 16.5% of residential heating will come from district heating (DH) in 2050. In this high mitigation scenario, the share of district heating would be 10% higher than the share reported in the Heat Roadmap Europe project[7]. DH can facilitate the decarbonisation of the building stock in dense urban areas, even with a decreasing heat density. Buildings in dense urban areas are particularly difficult to decarbonise, partly due to historic settings or special restrictions. On a European average, 8% of the final consumption is currently provided with derived heat. **By using DH, exhausts from individual boilers are relocated to centralised chimneys, which can reduce local pollutants such as dust, fine particles, sulphur dioxide and nitrogen**

[7] See more at: https://heatroadmap.eu

oxides. Compared with individual boilers, a central energy production can offer far more effective pollution prevention and control measures. DH is often based on the use of surplus heat which would otherwise be lost, e.g. surplus heat from industry, combined heat and power (CHP) systems, and thereby avoids the use of fossil fuels and related emissions. **DH does not depend on a specific fuel and is known as being very reliable because the heat is produced at multiple production facilities using a variety of fuels. DH also contributes to GHG reduction because of its long lifetime and high efficiency**.

Figure 18 simulates the number of deaths from air pollution in the EU, using the $PM_{2.5}$ index (fine particulate matter with a diameter of less than 2.5 µm), under the EUCalc 'Technologies and Fuels' example pathway. It is worth noting that this reduction reflects not only the benefits of increasing district heating, but also of improvements in other sectors, such as transport and power.

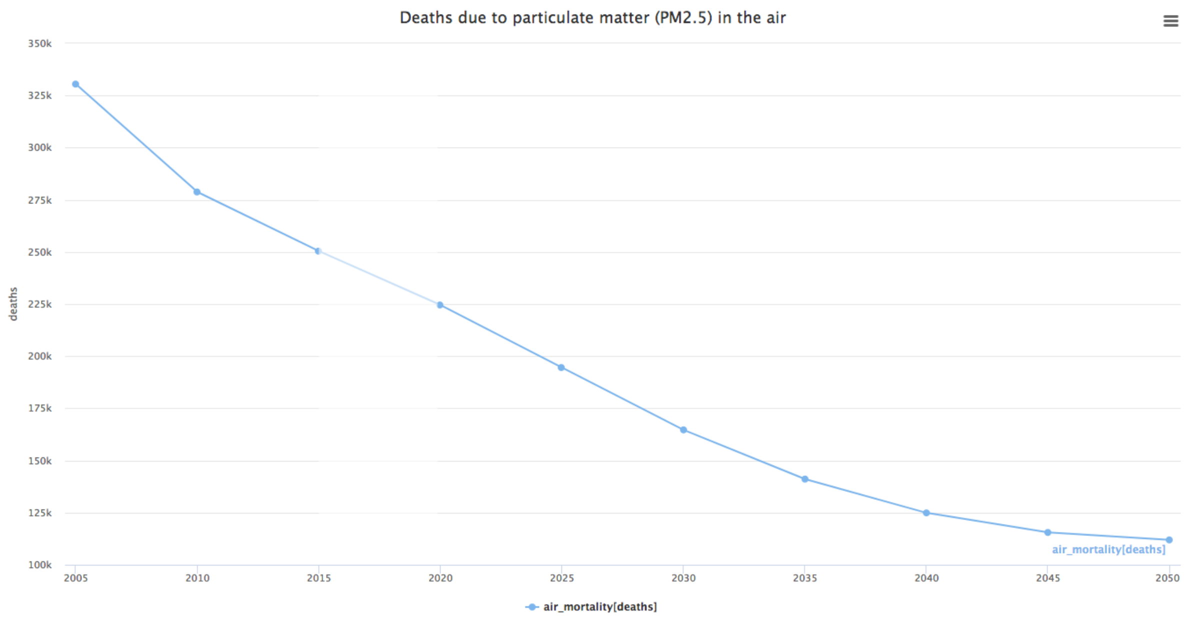


Figure 18: Number of deaths from air pollution in the EU ($PM_{2.5}$ index), under the EUCalc 'Technologies and Fuels'example pathway.

How will we heat our buildings and what type of fuels will be used in 2050?

Currently, several fuels are used for heating: 45% gas, 15% oil, 22% renewables, and other sources. **In our simulation for the *Technology and fuels* pathway, the use of fossil fuel would be almost completely phased-out in 2050, representing only 2% of the total energy consumed for heating in the building sector** (Figure 19 and Figure 20). The fossil fuel use reduction in 2050 would be -95% for gas, coal and oil, which would be substituted by ambient heat/heat pumps (60%), biomass (20%), solar (12%), geothermal (4%), biogas (2%), biofuel (2%). Moreover, heating technologies can have very different efficiencies and GHG emissions associated with them. Nowadays, the most common forms of heating in urban areas are district heating and gas boilers, whereas in rural areas, solid fuel boilers are most common. National policies on fossil fuel phase out may impact the evolution of the energy carriers and the technologies used for heating by 2050.

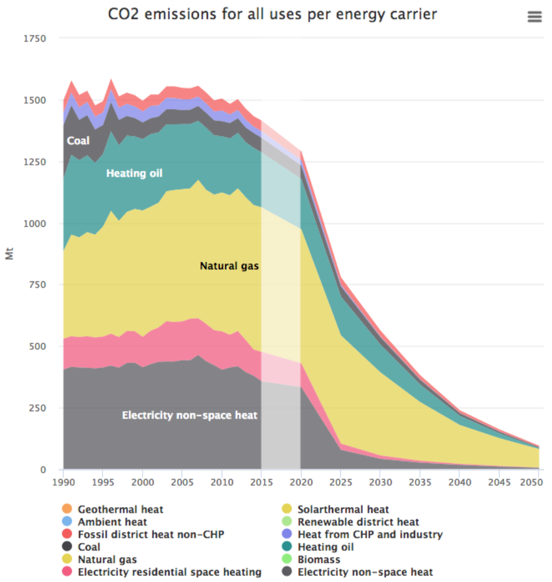


Figure 19: EU GHG emissions for all uses per energy carrier in buildings, under the EUCalc 'Technologies and Fuels' example pathway.

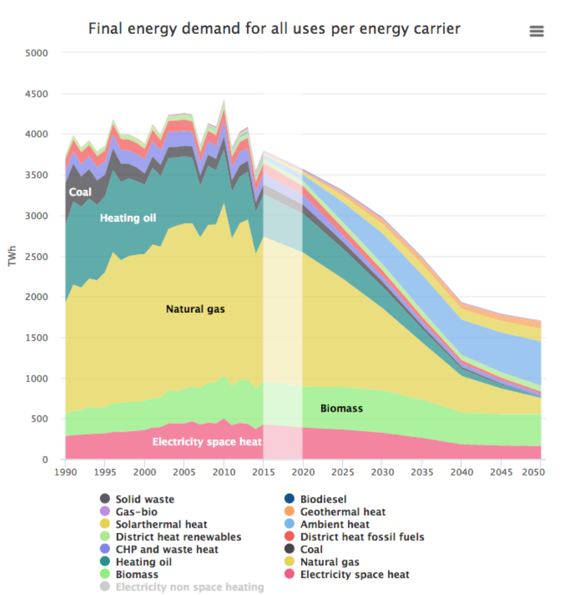


Figure 20: EU final energy demand per carrier in buildings, under the EUCalc 'Technologies and Fuels' example pathway.

How efficient will our heating and cooling systems be in 2050?

In our simulation, the current energy efficiency for heating and cooling systems in the building sector could be increased by 15% by 2050, affecting energy transformation, energy distribution and system control. The efficiency of boilers would increase slowly across the buildings stock to an average of 97% for gas boilers, 93% for oil boilers and 74% for wood boilers. Heating, ventilation and air conditioning (HVAC) systems have become more energy efficient over time. European and National policies for technologies substitution rate can have an impact on the average efficiency. Important aspects here would be the replacement of old and inefficient equipment, together with increased awareness for regular maintenance.

3.3 Changing our industries

Manufacturing is a key sector for carbon mitigation. **Actions should include improvements in material efficiency and switch, technology and energy efficiency, fuel mix, and the use of carbon capture in manufacturing and carbon capture to fuel**. Figure 21 summarises the changes that would be expected for different material products in industry up to 2050 as simulated from the *Technology and fuels* pathway. The EUCalc also provides the demand for various minerals necessary and required in the energy and manufacturing sectors.

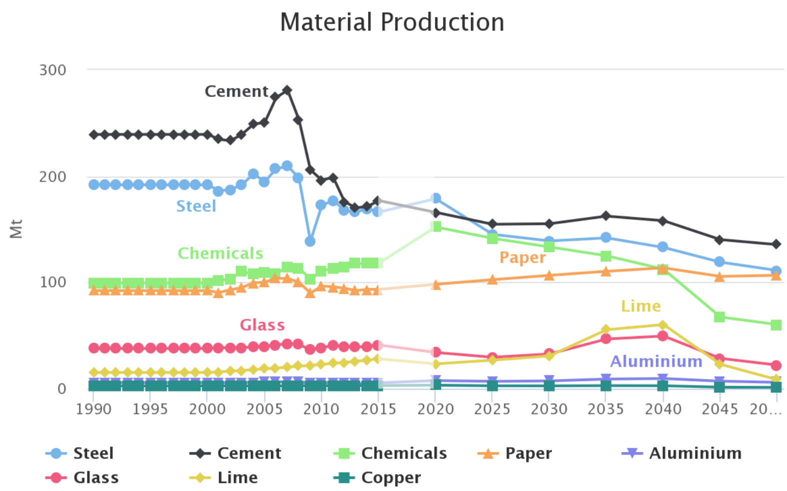


Figure 21: Material production in the EU manufacturing sector, under the EUCalc 'Technology and fuels' example pathway.

How can we use materials more sustainably? What level of material efficiency will we reach in 2050?

Selective Focus Photography Cement by Rodolfo Quirós

Increasing material demand poses challenges for sustainability. The IEA (2019), for example, suggests an increase in approximately 15% of CO_2 emissions in 2060 compared to 2017 level worldwide as a result of material demand. **In our simulation for the *Technology and fuels* pathway, the improvement rate would range between 10% and 33% due to smart products and material design, re-use of materials, and circularity concepts of additive manufacturing, leading to approximately 31% reduction in CO_2 emissions**. Material efficiency could reduce industrial emissions by 56 $MtCO_2eq$/year in steel, plastics, aluminium and cement production. This could be achieved by a number of strategies such as:

- Reducing the waste of materials in the manufacturing and construction processes: currently about 15% of buildings materials are wasted in construction according to Material Economics (2018);

- Reducing over-specification, for example, an estimate of 50% of the steel used in buildings is in excess to what is strictly necessary to meet structural needs); and/or

- Using more advanced materials, for example, the use of high-strength steel could enable carmakers to reduce vehicle weight by 25-39% compared to conventional steel (World Steel Association, 2016).

Figure 22 shows the associated GHG emissions per material produced in the industrial sector, according to the EUCalc Technology and fuels example pathway.

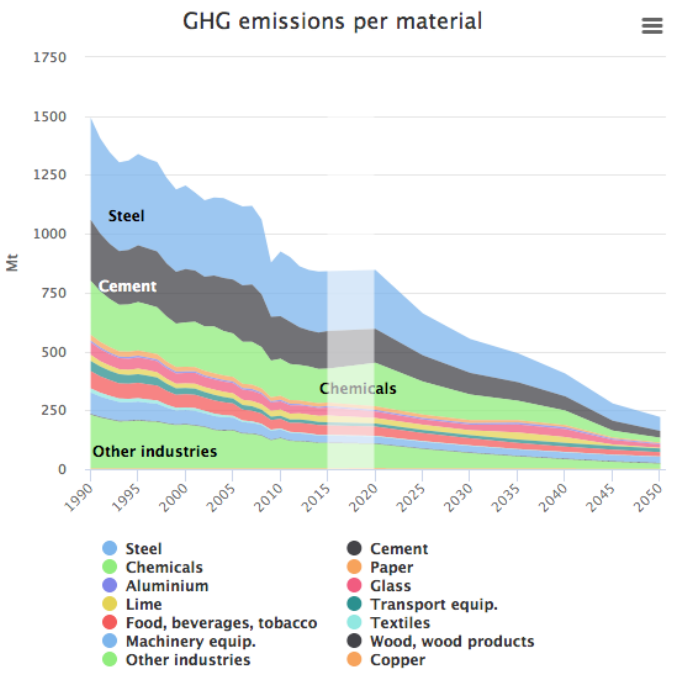


Figure 22: GHG emissions per material in the EU industry, under the EUCalc 'Technology and fuels' example pathway.

How will materials be replaced in 2050 without losing important functionalities?

Careful design may enable a product or a building to be produced using less materials, whilst also providing the same functionalities. Currently, an average gasoline vehicle for instance is made out of 67% iron and steel and 8% aluminium. **The *Technology and fuels* example pathway suggests that light-duty vehicles would substitute carbon-intensive materials in manufacturing by approximately 30% in 2050 compared to 2015. In this scenario, material switches would range from 10% (substitution of conventional wall insulation with cellulose) to 60% (substitution of concrete with timber in buildings)**. In transport lightweight aluminium replaces steels and other components, whereas in buildings natural fibres would replace fossil-based chemicals, and timber would substitute cement.

When cooling and heating requirements are comparable, wood-based constructions usually contain lower embodied CO_2 emissions than constructions based on steel, concrete and brick, according to a study by Sathre and O'Connor (2010). In vehicles, aluminium provides weight reduction compared with steel and, at the same time, it does not have the high costs of the more advanced materials (e.g. carbon-fibre reinforced plastics) according to Modaresi et al. (2014). Potentially, most car hoods, half of all door materials, part of trunks, roofs and fenders could be made of aluminium. Regarding timber, a common concern is the shorter lifespan of timber compared with the longer-lasting concrete, but treatments such as coating, impregnation, and chemical/mechanical modification could extend wooden building lifetime. **Several studies (e.g. Sathre & O'Connor, 2010; Werner et al., 2005; Upton et al., 2008; Gustavsson & Sathre, 2011; John et al., 2009) point out the importance of the switch to timber by comparing the embodied emissions of wood with other construction materials**.

How will emerging and energy-efficient technologies replace the existing ones by 2050?

The manufacturing of materials can be done by different technologies. Low-carbon technologies and the use of recycled materials can lead to a deep decarbonisation of the energy intensive manufacturing sectors. In 2015 the average share of the secondary production route of all technologies was about 16%, whereas in our simulation for the *Technology and fuels* example pathway, this share would be approximately 24% in 2050. **In this simulation, the iron and steel production processing would be heavily electrified based on hydrogen coming from renewables, and geopolymers would make up to 20% of total cement production, saving about 35% of CO_2 emissions**. Therefore, in this extreme scenario, energy-intensive industries would have an ambitious shift towards emerging, low-carbon technologies. **In the steel sector, the secondary route (scrap EAF (electric arc furnaces)), HIsarna process and hydrogen DRI (direct reduction of iron) would be responsible for 90% of total production, low carbon cement would make up almost 20% of total production, and the share of recycled paper would reach 90%**.

Currently, steel in Europe has been produced either by the primary route "BF-BOF" (blast furnace - basic oxygen furnace) or by the recycling route scrap-EAF, which has a much lower energy consumption (80% less). The share of scrap-EAF has increased from 20% in the 1970s to around 40% recently and is expected to continue to increase in the future due to a larger availability of scrap. Further innovative technologies for steel making are the hydrogen-DRI and the HIsarna process, which would allow at least a 20% decrease in energy use and emissions. In general terms, the prospective shift in the use of recycled material is conditioned by scrap availability and quality. A very conservative scenario estimates that the recycling route for steel will reach a share of up to 44% in Europe by 2050. The share of secondary aluminium produced in Europe has increased since 1995 and currently accounts for more than half of aluminium production. **An increase in growth is unlikely to be achieved due to the already high recycling rates and the reliance on a scrap stream from end-of-life products. The share of aluminium recycling route is estimated to reach 55% in Europe by 2050**.

How will energy efficiency evolve in the manufacturing and production sector in 2050?

In the *Technology and fuels* example pathway, most ambitious energy efficiency measures are implemented. **In this scenario, the range of increased energy efficiency would be between 10% (wood products) and 35% (food, beverages, and tobacco), whereas in energy-intensive sector the range would be between 13% and 25% in 2050**. A number of technology improvements can be applied across different sectors to increase efficiency and reduce emissions. There are cross-cutting technologies, which are relevant for more than one sector, like increasing boiler efficiency, employing operation & control techniques, using energy efficient motors, using variable speed drivers, reducing compressed air system leaks and efficient load management. Some sector specific measures include upgrading steam cracking plants to best practice technology in the chemicals sector, improved furnace design for iron and steel making or the usage of dry systems with preheaters and pre-calciners for the production of cement.

Some new technologies require large amounts of energy, such as the use of hydrogen for steel production, which requires a large amount of electric power for the production of hydrogen through electrolysis. The high demand for electricity can be met by using a decarbonised electricity mix. This technology can reduce emissions by up to 95% and decrease energy demand by up to 20%.

How will the fuel mix be in the manufacturing sector in 2050?

The decarbonisation of the manufacturing sector will require a shift towards a less-carbon intensive fuels, such as biomass or a decarbonised electricity mix. In 2015, the energy carried mix in each industry typically varied from one technology to the other. For example, in the steel industry the blast furnace-basic oxygen furnace (BF-BOF) route uses mainly coal for steel production, whereas the scrap-EAF (electric arc furnace) rout uses mainly electricity. **In our simulation for the *Technology and fuels* example pathway, the full potential of electrification of heat, use of zero-carbon hydrogen, and a switch to sustainable biomass are expected to take place, leaving very small share of fossil fuels in the energy mix, leading to an approximate saving of 38% CO_2 emission by 2050**.

One important decarbonisation option for the European manufacturing and production sectors is the substitution of fossil fuels used for energy and for feedstock with low carbon alternatives. There are several possibilities to reach this goal. The first one is the electrification of heat, which can be obtained by replacing furnaces, boilers, heat pumps running on fossil fuels with electric ones. A second possibility is the use of zero-carbon hydrogen to replace certain fuels used for energy or feedstock and the last one is the switch to sustainable biomass. The availability of low-cost zero-carbon electricity and biomass will influence the feasibility of these decarbonisation options. Availability can vary considerably among locations. Countries with high electricity prices and without biomass resources will have to rely on renewable electricity transmitted over long distances or imported biomass and zero-carbon hydrogen.

What percentage of carbon emissions from the manufacturing sector will be captured in 2050?

Carbon capture in manufacturing is a promising technology, but no commercially viable carbon capture technology options were in place in the European Union in 2015, although more than 20 small-scale demonstration CCS projects were already operating worldwide. Major research and development efforts are still required, as well as high investments. **However, in the *Technology and fuels* example pathway, as a very ambitious projection, in 2050 most carbon emissions resulting from industrial processes would be captured in energy intensive sectors (e.g. the production of lime, cement, iron and steel, paper and ammonia)**. In the lime sector, for example, up to 70% of carbon would be captured, eliminating all process emissions. In other energy-intensive sectors, significant GHG reductions would also be obtained: iron and steel sector (40% for blast furnace - basic oxygen furnace (BF-BOF); 20% in scrap EAF (electric arc furnace); 50% HIsarna ironmaking process; chemicals (45%); and cement sector (65%).

Carbon capture is a process whereby the CO_2 stream is captured from the off-gases. The carbon emissions can be either stored in a geological site (CCS - carbon capture and storage) or used (CCU - carbon capture and use). In the case of CCU the emissions can be used either directly (e.g. in the food industry), as feedstock for the chemical industry, or to produce synthetic fuels. Both CCS and CCU present issues, that could limit their possible future deployment. CCS can only be implemented in regions with adequate carbon-storage locations (e.g. isolated deep saline aquifers, oil or gas fields already depleted). **The process of capturing and transporting CO_2 is highly energy intensive. This results in high operating costs, on top of huge initial investment costs**. Both CCS and CCU require a regulatory framework and supportive public opinion before they can be developed. Should these issues be resolved, carbon capture could play an important role in delivering the deep emissions reductions needed across key industrial processes such as steel, cement and chemicals manufacturing. **Over the last two decades, a range of policy and regulatory measures have been adopted by governments in an attempt to facilitate and incentivise CC deployment**. In some jurisdictions, on the other hand existing laws prohibit the use of CC.

What percentage of carbon capture will be utilised for fuel production in 2050?

Although Europe has some few pilot projects regarding the use of carbon capture and use for fuel production, no commercially viable plant was available in 2015. However, several large-scale CCS projects are currently planned (e.g. five projects in the UK and two in the Netherlands). Compared to CCU, CCS requires less investment and energy consumption, whereas CCU contributes to the mitigation of fossil fuel demand and the alleviation of renewable intermittency by power-to-gas processes. **As an extreme simulation based on the *Technology and fuels* example pathway (Figure 23), 100% of the carbon captured is assumed to be used for fuel production in 2050, representing a trade-off between Carbon Capture and Storage (CCS) and Carbon Capture and Use (CCU)**. This scenario is assumed to be ambitious since the CCU has few advantages in terms of technological maturity and economic feasibility compared to CCS under the current energy system. However, the development of CCU is considered promising in correspondence to the development of intermittent renewable resources due to its potential for contributing to increasing energy storage demand. The output synthetic natural gas can be easily injected in the existing natural gas infrastructure facilitating the coupling of various energy, transport and industry sectors.

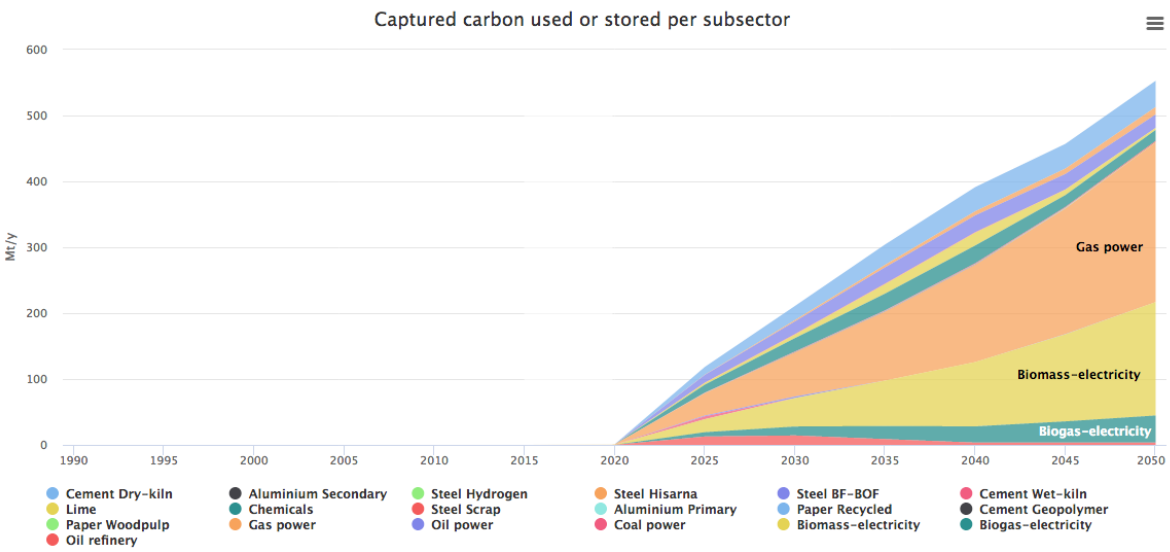


Figure 23: Captured carbon used or stored per subsector in the European Union (in MtCO2eq/year), under the EUCalc 'Technology and fuels' example pathway.

3.4 Changing our power sector

The power sector is responsible for a large amount of GHG emissions in the European Union. Decarbonisation strategies include changes related to coal phase out, carbon capture ration in power, nuclear, wind and solar energy, hydropower, geothermal and tidal energy, as well as the way we balance our electricity grid, including issues such as power intermittency and the charging of electric vehicles.

Will we still use coal to produce electricity in 2050? If not, when will it be phased out?

Europe is still reliant on coal for power generation, apart from the effort of some member states to increase the share of renewable energy in their respective energy mix. In 2015, about half of the electricity came from combustible fuels, including coal. A strong effort to mitigate carbon emission would require an urgent substitution of coal with renewable fuels and/or the use of carbon capture systems. **In our simulation for the *Technology and fuels* example pathway, which represent a very ambitious carbon mitigation effort, coal would be phased out by 2025 in most EU Member States** (Figure 24). In this scenario, coal power plants would be closed prior to phase out policies or before the forecasted closures due to market developments.

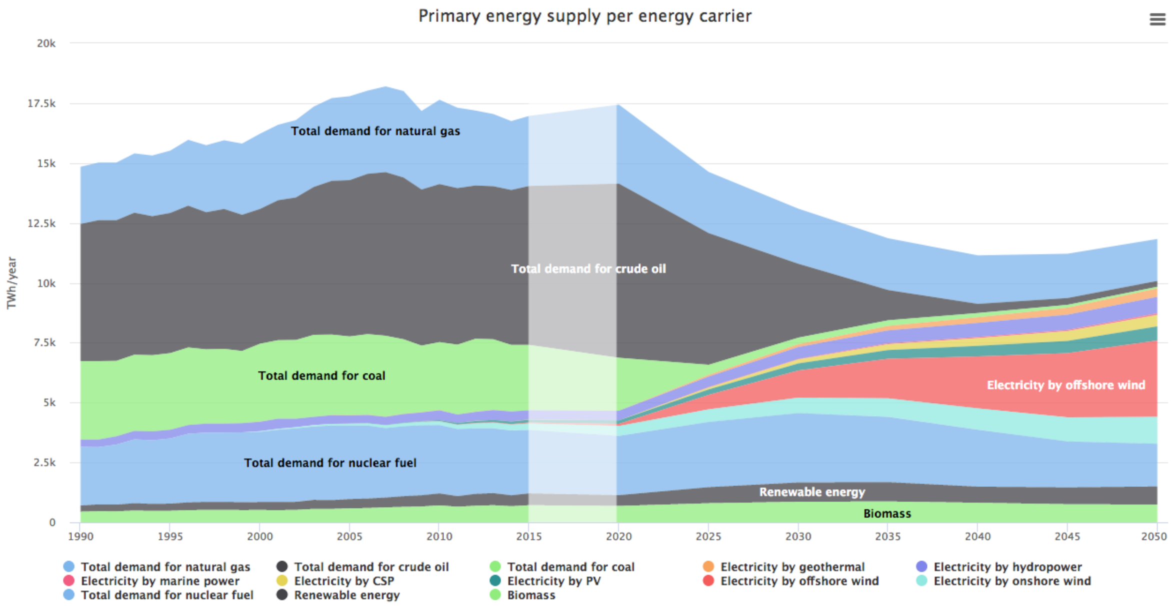


Figure 24: EU primary energy supply per energy carrier, under the EUCalc 'Technology and fuels' example pathway.

Coal based power generation is responsible for most of emissions from the electricity generation sector, thus intention and timing of phase out is considered decisive for all decarbonisation pathways. In 2015 there were 280 coal power stations in the EU with a total of 162.7 GW installed capacity. The coal power stations in 2015 were situated in 22 Member States; the only countries without any coal power station in 2015 were Cyprus, Estonia, Latvia, Lithuania, Luxembourg and Malta. Since then, also Belgium closed its only coal power plant, going coal free. On the other hand, Germany and Poland alone account for nearly half of the EU's installed capacity (51%) and more than half of yearly emissions (54%) of all coal-fired power plants. **Nevertheless, due to ageing and decarbonisation actions, conventional power sources such as fuel oil and coal continued to decommission more capacity than they install. However, the rate of decommissioning is slower than the urgency of climate actions would require; thus, phase out plans are an essential part of decarbonisation**. National coal phase out plans are decisive in the future scenarios of coal-based power generation at country level.

Moreover, in terms of lifetime, two-thirds of the coal power plants were 30 years old or older in 2015. Comparatively, little new capacity was installed during the 1990s and early 2000s. However, in the last decade, a considerable amount of new capacity has been built in Poland, the Netherlands, Italy, and especially Germany. Unless these plants are retired before the end of their lifetime, emissions will be locked in the system longer than what would be consistent with the EU's GHG emissions reduction targets. **This process can be sped up by implementing the coal phase out policies which are already present in multiple countries of Europe. The picture varies between Western and Eastern Europe. Western Europe is accelerating its coal exit. Climate change and air pollution combined action to specifically phase out coal-fired power generation is impacting coal demand**. Along with the expansion of renewables, these policy efforts will eventually push coal phase out of the Western European power mix. In contrast, most countries in Eastern Europe have not announced phase out policies and a handful of new coal power plants are under construction in Poland, Greece, and in the Balkans. Some countries in Eastern Europe are among the few places in the world where lignite remains the cornerstone of the electricity system.

What percentage of GHG emissions coming from the power sector would be captured in 2050?

The European Union has been investing in carbon capture technologies in the power sector, but as of 2015 only small-scale demonstration plants were installed. Carbon capture technologies capture CO_2 emitted from power plants and industrial facilities. Hence, the goal of carbon capture is to prevent CO_2 from reaching the atmosphere and to either store it in suitable underground geological formations or use it in chemical conversion processes. **In the *Technology and fuels* example pathway, about 80% of those emissions from power generation using fossil fuels would be captured in 2050**, which represents a very high ratio. In scenarios where fossil fuels would still be used in the power generation mix, carbon capture has a role to play in reaching climate mitigation objectives. However, with the growing share of renewable energy and policy intentions aimed at a quick phase out of coal, these expectations may not be met and investments in carbon capture may well become stranded assets. As of 2018, there were no existing commercially viable uses of carbon capture and storage projects in the EU. On the other hand, the use of carbon capture in biomass-based thermopower (Bioenergy with Carbon Capture and Storage – BECCS) could provide negative emissions and, as a concrete example, an ongoing related project[8] has been developed by Drax Power Ltd in the United Kingdom, based on the availability of biomass in both the domestic and international market (Woods et al., 2011).

As stated in 'A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy', which is a communication from the European Commission (EC, 2018, ref. COM(2018)773), carbon capture was previously seen as a major decarbonisation option for the power sector. However, this potential currently appears to be low. Nevertheless, carbon capture deployment still has a role to play, especially in energy intensive industries and - in the transitional phase – to produce carbon-free hydrogen. **Apparently, the main application area of carbon capture is no longer in power generation, due to plant phase out plans**.

What role will nuclear energy play in 2050?

The expansion of nuclear power capacity is an issue subject to high controversy across the EU Member States and worldwide. In 2015, around a quarter of the total electricity produced in Europe came from nuclear power plants and a substantial reduction in total capacity is expected by 2050. However, as suggested in the *Technology and fuels* example pathway, this phase out may be slow under a high mitigation effort for climate change. **In this scenario, nuclear maintenance, planned nuclear power plants would be implemented in line with nuclear capacity decreasing to 76% of the base-year capacity** (Figure 25). Thus, this pathway assumes 10+ years delayed nuclear phase out and in countries where new nuclear power plants are planned, these would be started in time, which in some nations would result in the expansion of nuclear capacities.

Nuclear Power Plant by Markus Distelrath

[8] See more at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/

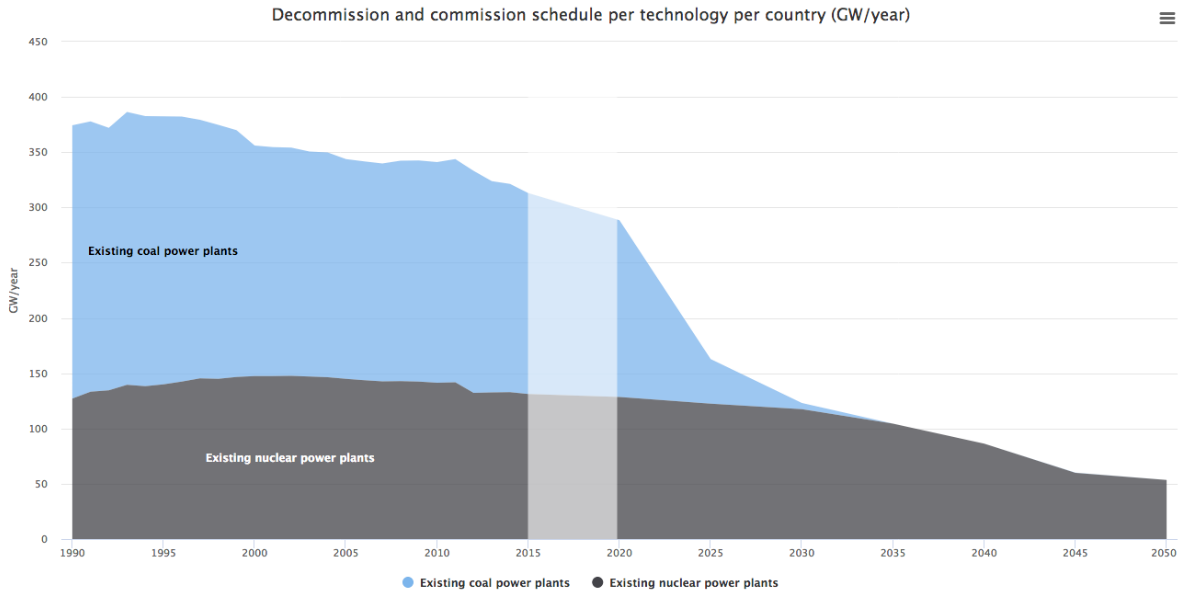


Figure 25: Decommissioning trend for coal and nuclear power in the EU, under the EUCalc 'Technology and fuels' example pathway.

Nuclear power plants using the process of nuclear fission are a controversial source of electricity, as the large-scale decarbonisation potential is coupled with concerns of operational safety and waste management. According to the World Nuclear Industry Status Report (WNISR, 2019), 128 reactors were in operation in the EU in 2015, of which almost half (58) were in France. In total, these 128 reactors have a capacity of 119.7 GW, generating roughly a quarter of the electricity production in the EU. **Nuclear power generation can significantly contribute to decarbonisation, offering GHG emission-free baseload power, let alone emissions related to plant construction and decommissioning. However, due to different concerns, some countries have decided not to use it or to phase out existing capacities. Because of the ageing and phase out policies, nuclear power generation is foreseen to decrease in the EU, but policies and plans vary between Member States**. Historically, the number of reactors in operation has been decreasing since 1989 in the EU, whereas the vast majority of the facilities, 109 units or 85%, are located in eight of the Western European countries, and only 19 units are in the six newer Member States using nuclear power.

How much wind power will we generate in 2050?

Wind power capacity has significantly been expanding in the European Union. In 2015, around 10% of the electricity generated came from wind power, i.e. 140 GW. **Consequently, the EUCalc *Technology and fuels* pathway shows that total onshore and offshore wind power capacities combined would exceed 1,400 GW in the EU in 2050** (Figure 26). This scenario is extremely ambitious towards the use of wind power within the EU.

Photography of Three White Windmills. Source: Pixabay

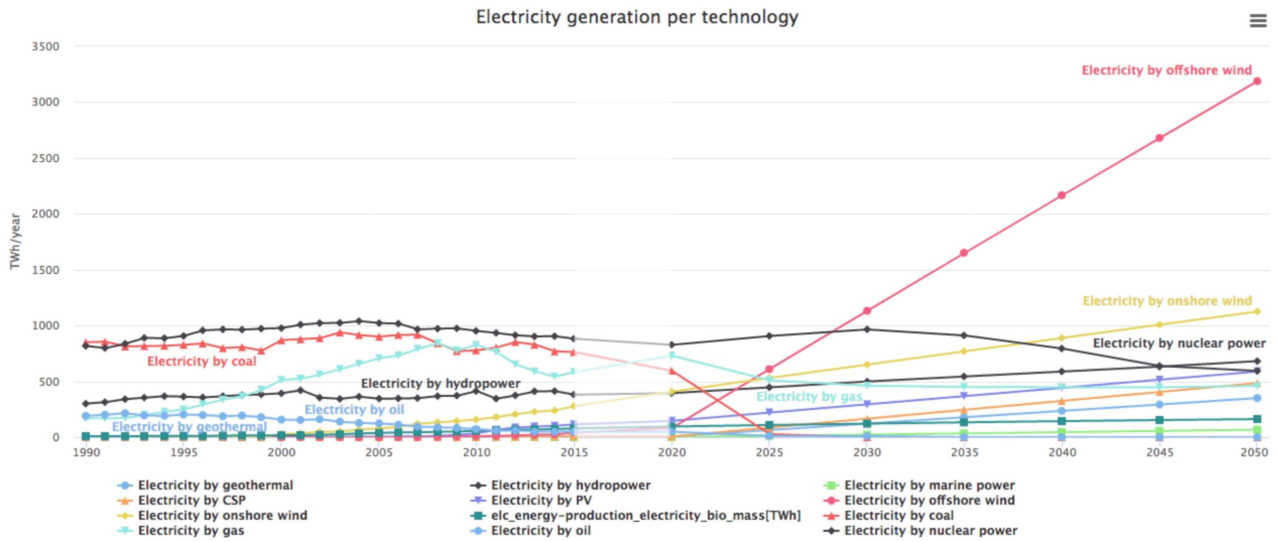


Figure 26: Electricity generation per technology in the EU, under the EUCalc 'Technology and fuels' example pathway.

In the past years the EU has seen a significant increase in renewable-based power generation, especially because of policy incentives, such as the European Commission Directive 2009/28/EC and the policy framework for climate and energy in the period from 2020 to 2030 (COM/2014/015 final), as well as the ever decreasing costs and economic maturity of the technologies. **This growth is especially significant in the case of wind power generation that has gone from 2.4 GW in 1995 to 154.3 GW in 2016. These trends are expected to continue in the future with renewables becoming more and more competitive**. Wind power already accounts for one third of all new power installations in the EU since 2000. Due to the continuous increase of wind power capacities, with a total net installed of 169 GW in 2017, wind energy was the second largest form of power generation capacity in Europe, fast approaching natural gas installations. Most of the installations were onshore, but offshore wind power capacities are also growing.

On the other hand, this substantial increase in wind power capacity would significantly influence the electricity grid and its operation, leading to growing intermittency. More flexibility will, therefore, be needed in the system, changing drastically the grid operation from centralized, as it is now, to a decentralized form. In addition, greater and more efficient storage capabilities will be required to counter-balance the electricity grid.

How much solar power will we generate in 2050?

Blue Solar Panel Board. Source: Pixabay

In recent years, the EU has seen a significant increase in solar-based power generation. Photovoltaics (PV) has gone from 0.05 GW in 1995 to 103.1 GW in 2016, representing about 3% of the total electricity generated in Europe. **Under the *Technology and fuels* example pathway, by 2050 this capacity would be close to 700 GW, including PV and CSP (concentrating solar power) systems, representing a major climate change mitigation effort**. Solar power generation can be the cornerstone of a decarbonized electricity system in many EU countries. PV has seen an incremental growth exceeding in 2014, the 2020 National Renewable Energy Action Plan target of 83.7 GW. However, the distribution of installed capacities is very uneven between the Member States. Only two countries, Germany and Italy installed more than half of the total European PV power plant stock, followed by the UK and France. CSP technology is present with low capacities in Europe, in 2015 installed CSP capacity was of 2.3 GW with the bulk of these coming from Spain, and with a few pilots in Italy (7.5 MW), France (0.75 MW) and Germany (1.5 MW). In contrast to what was previously mentioned for the wind power expansion, this would require investments in energy storage in order to regulate its intermittency in the electricity grid.

How much power will be generated by hydropower, geothermal and marine technologies in 2050?

Total hydropower, geothermal and marine capacities would be close to 300 GW by 2050, under the *Technology and fuels* example pathway. Currently, hydropower provides the largest source of renewable electricity production in the European Union, given that its market is already highly developed. In 2015, the EU had a total 120 GW of hydropower (excluding pumped storage) with 86 GW of that found in only 6 countries: Austria, France, Italy, Spain, Sweden and Switzerland. This is more than 10% of the total electricity generated in EU28+Switzerland, whereas the electricity coming from geothermal and marine technologies accounted for only 0.95 GW and 0.25 GW, respectively, in the European Union.

The installation of these technologies (hydro, geo and marine power) can in some cases play an important role in decarbonization pathways. Unlike hydropower, penetration of geothermal and marine energy capacities is still low (neither of them reaches 1 GW at EU level), as it is limited to countries with certain geographical and geological conditions. The term marine energy includes multiple technologies, although the only significant installation within the EU is found in France with 240 MW capacity. Furthermore, the bulk of geothermal capacities in the EU is limited to one country - Italy has 879 MW of geothermal electricity production - with a few small plants ranging 1-27 MW in Austria, Cyprus, France, Germany, Greece, Portugal and Romania. **Regarding investments in the hydropower sector, these have been primarily focused on pumped storage projects, as it is currently the only flexible carbon-free technology in the electricity system that exists in large scale**.

What electricity portfolio will be used to manage the needed flexibility of the electricity grid as intermittency grows due to the high share of renewable energies?


Silhouette of Electric Tower by Skitterphoto

The balancing power potential could exceed 500 TWh at the EU level, if all storage technologies grow according to their most ambitious trajectories by 2050, which represent a very high projection, based on the *Technology and fuels* example pathway. This scenario would require a transformational change, including significant cost reduction for some technologies, very fast and extended deployment of infrastructures, major technological advances, and societal changes. **A decarbonised power system in the EU will depend on a large share of non-dispatchable, weather dependent sources, primarily solar and wind power. Hence, it is key to increase the overall flexibility of the power system**. Flexibility solutions (e.g. energy storage technologies) can provide a variety of flexible services, including provision of operating reserves and shifting energy over time to better match generation and load. Some examples of these technologies are pumped hydroelectric storage, battery, flywheel, compressed air storage and power-to-X technology. Otherwise, gas-based power would be probably required to counter-balance the intermittency from renewables in electricity grid. Alternatively, biomass-based electricity can also offer a dispatchable power generation capacity.

How are we going to charge electric vehicles (EV)? How will EV contribute to grid flexibility in 2050?

With a fast increase in the EV fleet in the European Union by 2050, **significant investments would be required so that the EVs could be charged in an intelligent manner and, thus, making the storage potential of EVs available for flexibility purposes**. The charging technologies and strategies may vary, for example, home charging when cars are charged in the after-work hours from home; delayed home charging when cars are charged during the night hours when demand for other forms of electricity consumption is low; home and work charging when cars are charged also during work hours; and finally intelligent charging when the charging time of cars adapts to the availability of extra power on the grid. **The number of electric vehicles on the road is forecast to grow significantly, and thus their impact on the grid and demand profiles is also increasing**. Nevertheless, the charging of EVs can adopt to the daily routine of the users and can be adjusted based on the state of the electricity system. Thus, with proper incentives, a significant demand side management potential is expected. This will be urgently needed, as the widespread adoption of electric vehicles could increase the risk of overloading the power grid by inflating peak demand.

4 Pathways for Changes in Land Use and Food Production

This section outlines how changes in land use and food production, alongside behavioural changes can affect GHG emissions in Europe. An overview on the main related issues to land, food and biodiversity conservation is also provided. This scenario is called *'Behaviour and Land-Food'* in the list of example pathways available in the Transition Pathways Explorer of the EUCalc model, and it portraits an Europe where maximum efforts in *Key behaviours* (as discussed in section 2) and *Land-Food* are undertaken and where efforts in *Technology and fuels* evolve as in the *EU Reference Scenario* (as shown in section 1). **The *Land-Food* pathway reflects the ongoing debate that brought about the IPCC Special Report on Climate Change and Land (IPCC, 2019), representing a Europe where land and food production become 'climate-smart', which may not necessarily result in lower GHG emissions, depending on the issue addressed**. The EUCalc modelling approach for land and food builds on previous experiences from the Global Calculator's land/food/bioenergy/forestry model (Strapasson et al., 2017) and the EU Land Use Futures (EULUF) model (Strapasson et al., 2016).

Does changes in land use and food production associated with behavioural changes really affect carbon mitigation pathways?

Figure 27 demonstrates that changes in the way we use our land resources, produce our food, and our lifestyle choices (e.g. dietary patterns) can significantly affect GHG emissions in the European Union. Therefore, it is not only the industry, power and transport sector that matter for climate change mitigation, but also the management of our natural resources, agriculture, livestock, forestry, and behavioural choices. In fact, **land use is fundamental for achieving a net-zero GHG emission, given that it is the only sector that can effectively provide negative emissions at scale, apart from potential geoengineering technologies that are highly speculative to date** (and not addressed in the EUCalc).

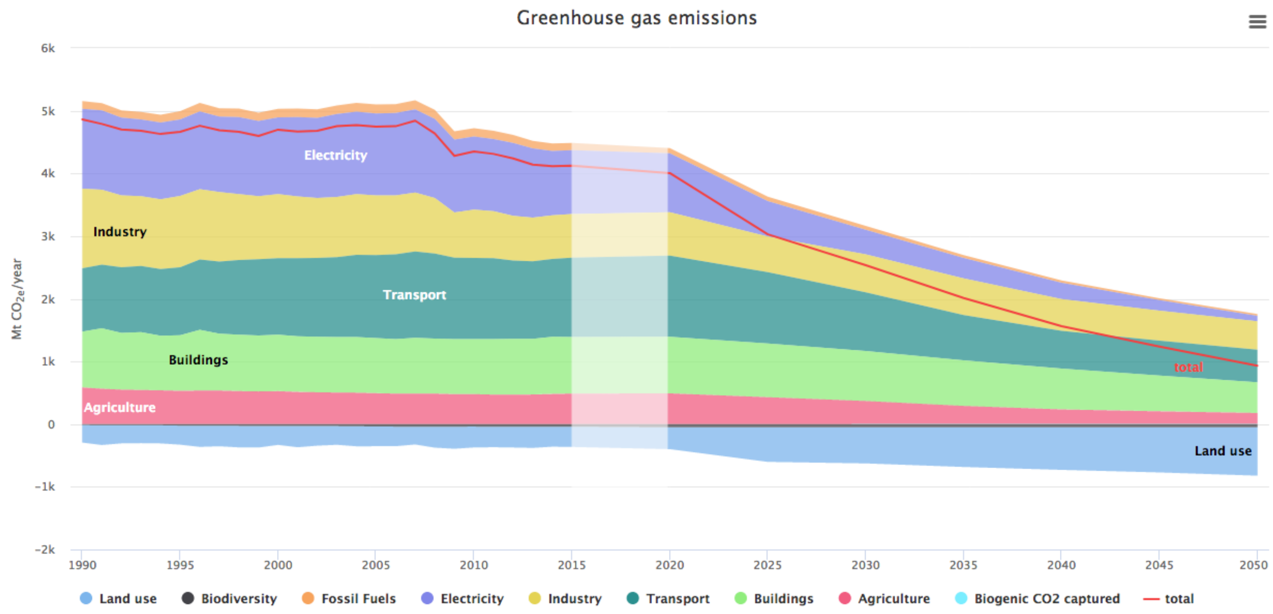


Figure 27: EU GHG emissions reductions from changes in 'Behaviour and Land-Food', EUCalc.

4.1 Changing our land and food system

Land use and food production systems are highly complex issues to model while estimating carbon mitigation pathways by 2050. In the EUCalc, the main issues for this sector were climate smart production of crops, livestock and forestry, alternative protein source for animal feeding (livestock production), land use management, bioenergy capacity and the prioritisation of biomass allocation according to different end-uses.

How sustainable and productive will crop production be in 2050?

Selective Focus Photography of Wheat Field. Source: Pixabay

Crop production in the EU is based on different technologies, productivity ranges, and plant types. By 2050, significant changes in the way that we have agriculture may occur, from a high intensification of conventional practices to an increase in agroecology and crop-rotation with an emphasis on the conservation of natural resources. These changes also include the way we manage our food waste and losses from the production side (on farm), as well as the use of fertilisers, pesticides, crop yields and energy. **In our very ambitious simulation (i.e. *Behaviour and Land-Food* example pathway), the whole European agricultural production system would follow agroecology standards by 2050**. The use of chemicals in agriculture would be fully banned and replaced by integrated pest management. Food waste and losses are limited to a third of the previous level or about 6 times lower compared to 2015. In contrast, this extensive approach may lead to a decrease in crop yield by approximately 20-40% by 2050 (compared to 2015), but the agriculture land potential for carbon storage would be fully exploited, in line with the 4 per 1000 initiative[9]. **This example pathway also suggests a decrease in food consumption, especially in per capita meat intake**. As a result, this will lead to a decrease in the use of animal feed for livestock production, hence this scenario represents an ambitious situation. The results for this pathway are summarised in Figure 28.

[9] See more at: www.4p1000.org

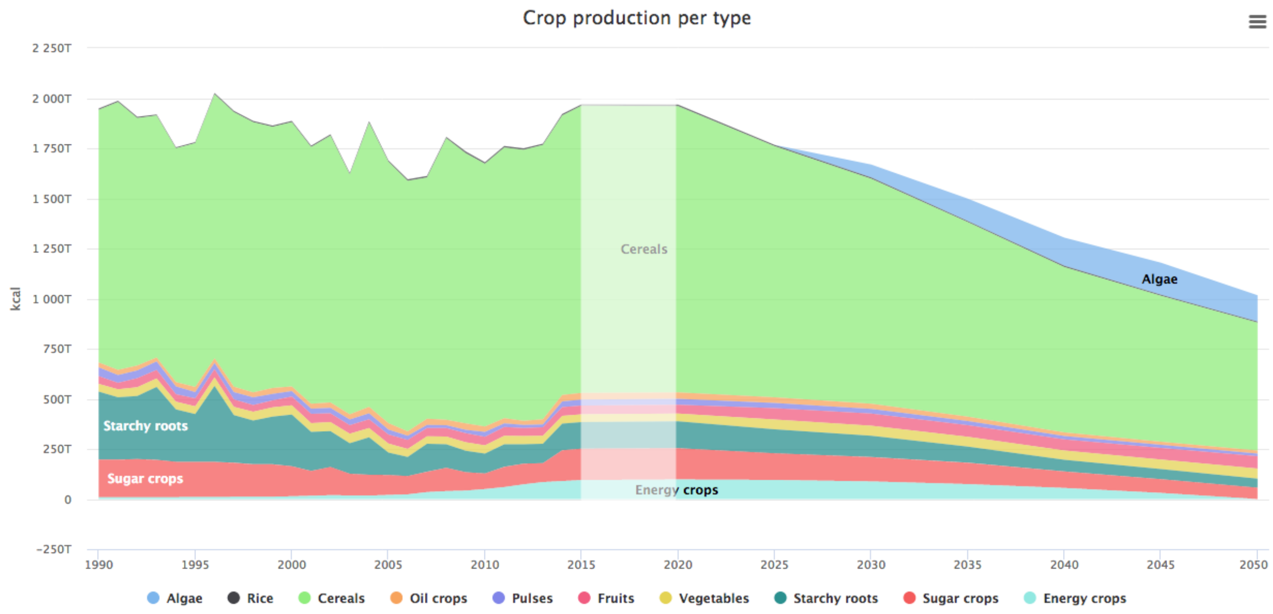


Figure 28: Crop production per type in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

According to the UNFCCC (2019) GHG inventory, the agriculture sector emits 438 $MtCO_2eq$/year (around 10% of the total European Union GHG emissions), whereas crop cultivation represents about 40% of the agriculture sector emissions in 2015. The European agricultural production system is mostly driven by the EU 'Common Agricultural Policy' (CAP). Therefore, it is assumed that the crop production system pattern will follow the current trends until 2021 at least. **The overarching concern is to sustainably feed people whilst also supplying non-food agricultural commodities to substitute fossil-based energy and material, as well as preserving and enhancing the sustainable use of natural resources, the agricultural resilience to climate change and, ultimately, contributing to climate change mitigation**.

How sustainable and productive will livestock production be in 2050?

Livestock production can be based on various agronomical systems. This can affect how land resources are used (e.g. feedlot vs. extensive grassland, and integration systems such as silviculture), livestock yields, slaughter rate, among other issues. Similar to the discussions presented for crop production, **in our simulation the *'Behaviour and Land-Food'* example pathway, by 2050, the whole European agricultural production system would follow agroecology systems**. Grasslands would be used more extensive, with a maximum livestock population of 1 Livestock Unit per hectare (LSU/ha). Livestock yields would remain constant compared to 2015, and an increase of the livestock slaughter age would meet organic farming systems. This scenario also predicts a substantial reduction in meat consumption, leading to a decrease in total livestock population (Figure 29). This is just an illustrative pathway and several other scenarios are also possible to occur. As with crop production, food losses and waste at farm level would be much lower than in 2015. **It is also worth noting that livestock production may also be sensitive to the demand of meat, i.e. changes in dietary patterns, as well as imports and exports of meat and feed products**.

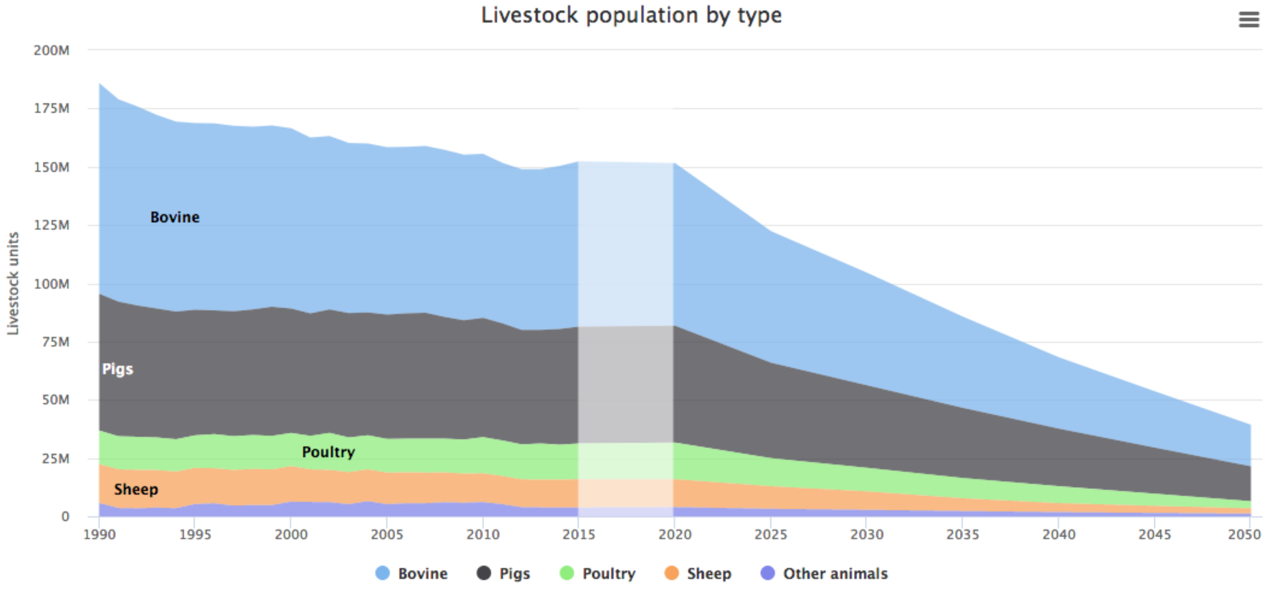


Figure 29: Livestock population in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

Will we use alternative protein sources for livestock feeding in 2050?

Livestock consumes more than 60% of the crop produced in Europe, which affects land demand, both inside and outside the EU. Animal-feed demand has been substantially been met through imports (mainly grains), which is not necessarily sustainable, including risks of deforestation abroad, biodiversity erosion, and GHG emissions from unsustainable practices. Therefore, some alternative protein sources have been considered to help reduce the dependency on grass and crop production for animal feed. **Insect farming and algae-based meals are promising options to produce a large amount of animal feed and by-products while using limited amount of lands**. On the other hand, in 2018, insect production reached only 2000 t/year in Europe. By 2050, this production may be no longer deployed, but it can also largely increase. **In our simulation for the *'Behaviour and Land-Food'* example pathway, by 2050, the deployment of insect and microalgae meals would occur in a large extent**. Microalgae meals would reach approximately 5% for poultry, 10% for ruminants (cattle, sheep, goats), 25% for pigs, and 30% for aquaculture, whereas insect meals would reach up to 30% for poultry, 33% for pigs, and 40% in aquaculture. To set this maximum use of alternative feed intake for each livestock type, the EUCalc assumes nutritious limitations regarding animal health and food output quality.

Moreover, the use of alternative protein sources for livestock production may increase the amount of spare lands in Europe. Through a better land management system, new prairies, reforestation and afforestation may also occur. Moreover, microalgae and insect biomass by-products may enable an additional production of bioenergy (e.g. microalgae oil), insect manure (as an organic fertiliser for agricultural soils) and waste valorisation (through insect farming). The use of yeasts (e.g. from biorefineries, and beverage production) as animal feed is also a possibility, although this was not considered in the current version of the EUCalc.

How sustainable will forest management be in 2050? How will this affect forest's carbon sink potential?

Enhanced productivity management of forests could increase the gross biomass increment by 2.5 m^3/ha, added to the 8.8 m^3/ha average in the EU28 in 2015. **In our 2050 simulation under the *'Behaviour and Land-Food'* example pathway, climate-smart forestry practices would be deployed in all European forests by 2050, leading to maximising biomass production and carbon pool potential in Europe**. This affects the gross biomass increment, natural losses (including resilience against natural disturbances) and the harvest-rate. This pathway also suggests crop and livestock yield gains as well as a reduction in per capita meat consumption across the EU, freeing up areas for forest expansion, as shown in Figure 30.

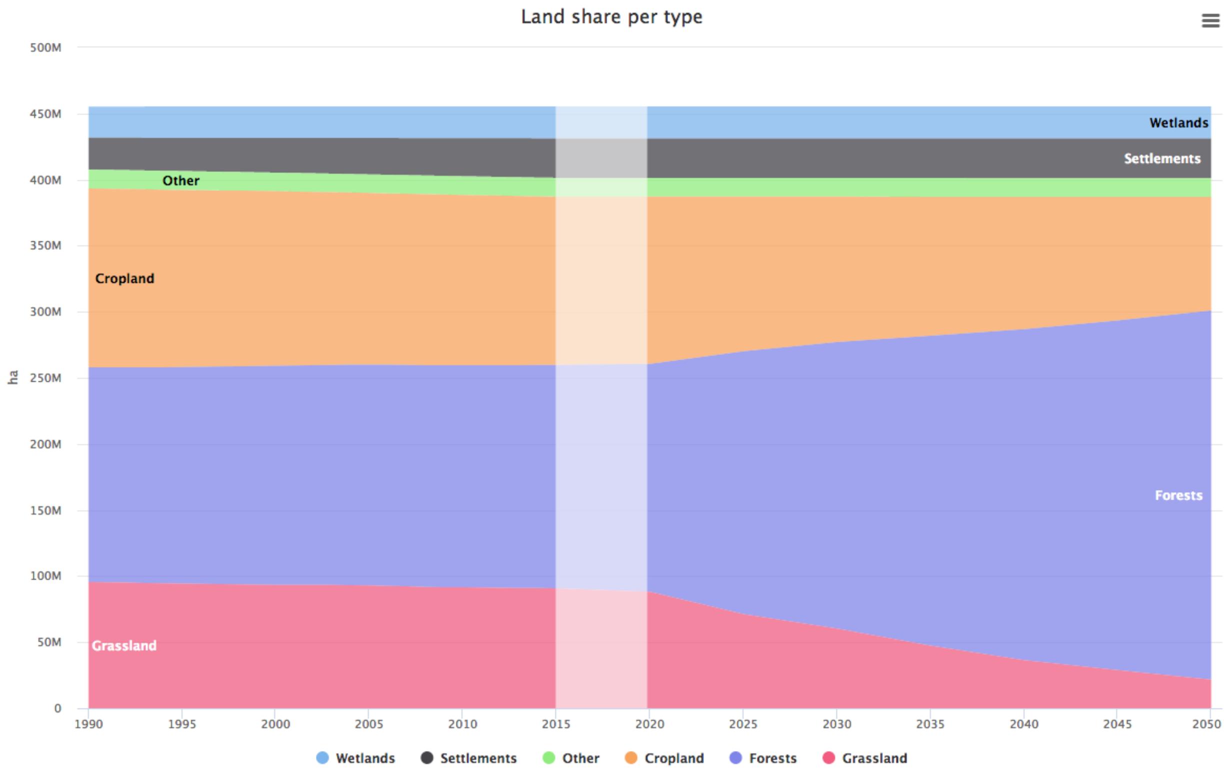


Figure 30: Land use in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

The European forests enabled the capture of 419 $MtCO_2eq$ in 2016 in the EU 28+Switzerland, which represents almost 8% of total GHG emissions. **Climate smart forestry includes a set of enhanced management practices, such as full-grown coppice and sustainable harvest rate, which can enable an additional 440 $MtCO_2eq$ mitigation potential by 2050**.

How much will bioenergy contribute to energy supply by 2050?

Bioenergy can play an important role to help mitigate emission in the European Union, from liquid biofuels (e.g. ethanol, biodiesel, biogasoline, biojetfuel) to solid biomass (e.g. wood pellets, chips and logs, crop residues) and biogas (e.g. anaerobic digestion from landfill wastes, sewage, animal residues). Whilst liquid biofuels are focused on the transport sector, solid biomass and biogas are focused on power generation (bioelectricity) and heating. **In our simulation for the *'Behaviour and Land-Food'* example pathway scenario, total bioelectricity capacity would increase according to the most ambitious trajectories found in literature, reaching approximately five times existing capacities in 2015**. Bioelectricity capacity has been increasing at 13% a year since 2005. As the extrapolation of this trend is unrealistic, *EU Reference Scenario* and literature for perspectives of bioenergy capacity trends were used to estimate possible future trends of bioenergy by 2050.

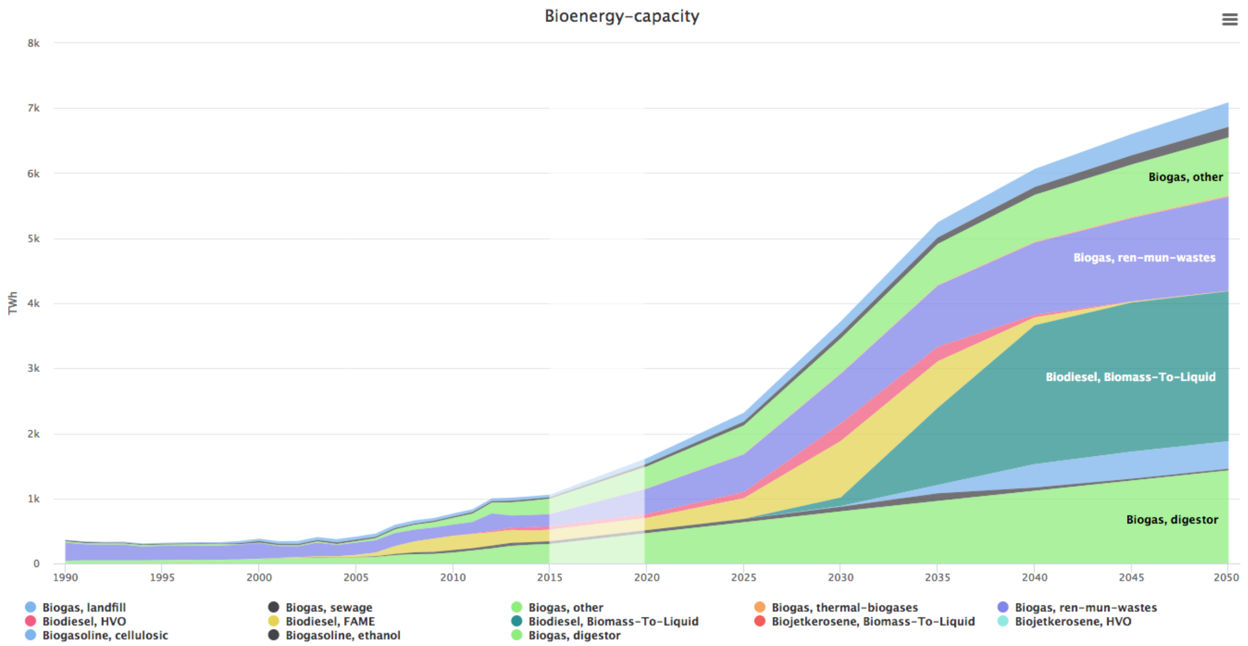


Figure 31: EU bioenergy capacity according to different technologies and fuels, under the EUCalc 'Behaviour and Land-Food' example pathway.

Bioenergy expansion in Europe is very connected with policy regulation at EU and Member State levels. While countries such as Germany and France are very prominent in the use of bioenergy, other Member States have a small share of its use in their respective energy mix. Europe is amongst the top bioenergy producers worldwide, just behind the United States and Brazil. The global potential for the sustainable production of bioenergy may increase from approximately 60 EJ in 2015 to 70EJ in 2050 under a business usual scenario, to 170 EJ in 2050 under high mitigation scenario or up to 360 EJ in 2050 under an extreme mitigation scenario, as demonstrated by Strapasson et al. (2017), using the Global Calculator[10]. The EU may continue to play a major role in the international bioenergy market.

Moreover, the transport sector is highly reliant on fossil fuels (e.g. gasoline, diesel, jet fuel) and, therefore, liquid biofuels can help mitigate carbon emissions in this sector. While some technologies can be mostly electrified (e.g. light-duty vehicles, trains), others are more challenging to be decarbonised (e.g. aviation, maritime freight, heavy-duty road transport), requiring a liquid fuel alternative at least in short and mid-term. Besides, the use of solid biomass associated with carbon capture and storage (BECCS, aka Bio-CCS) or with carbon capture and use (Bio-CCU) systems can provide either negative or low-carbon emissions.

How will biomass feedstock by-products and residues be driven towards other possible uses in 2050?

Biomass by-products and residues can be used as bioenergy sources without demanding additional land use. For example, animal fats were used to produce approximately 1 Mt of biodiesel in the EU in 2015. On the other hand, biomass by-product and residues can be used to reduce preventively an additional crop demand, for example, as a source of biomaterials and animal feed, or to be recycled in the form of organic fertilisers, biogas and digestate.

Following the European Union approach to waste management (Waste Framework Directive, 2008/98/EC), a hierarchy can be set for the use of the available biomass between different valorisation pathways:

[10] The Global Calculator is available at: http://tool.globalcalculator.org

- Prevention options include the reduction of waste, the redistribution to people or animals (e.g. pet food, livestock feed);
- Recycling options include the use of biomass for composting as organic fertiliser and possibly for anaerobic digestion;
- Recovery options are focused on energy recovery; and
- Disposal options include incineration, landfill and sewer.

Hence, the allocation of biomass by-products and residues can follow different routes. The 'Behaviour and Land Food' example pathway, for instance, simulates a 2050 scenario, in which the allocation of biomass uses would be towards prevention-recycling. Similarly, food crop-based biofuels and dedicated energy crops would not be used as bioenergy feedstock (apart from residues, by-products and wastes), whenever the latter cannot be used as biomaterials or fertilizers. It important to emphasise that this pathway is just a simulation exercise and may not necessarily represent the best option for carbon mitigation. Figure 32 shows the main bioenergy sources and technologies according to this example pathway.

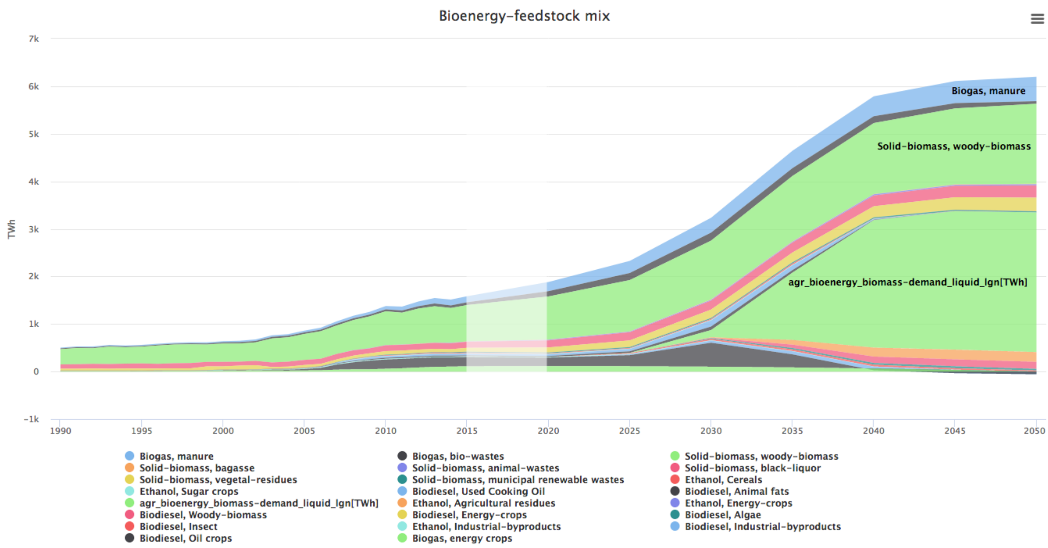


Figure 32: Bioenergy feedstock mix in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

How will land use change by 2050? How will this change affect carbon dynamics and GHG emissions?

Land use and land use change are affecting the carbon stocked in the soil and biomass availability, both positively (e.g. afforestation) and negatively (e.g. deforestation). **Land use, land use change, and forestry (LULUCF) is a key pillar to enable net-zero emission pathways as one cannot completely reach zero emissions by 2050 without them**. This occurs thanks to the natural carbon cycle. The oceans, lands and forests constitute major natural carbon sinks that can offset CO_2 emissions. Currently, LULUCF enables offsetting 258 $MtCO_2eq$ in the EU. By 2050, depending on scenario setting, this offset could be even larger. By increasing crop and livestock productivity combined with a reduction in land demand via behavioural changes (e.g. low meat consumption), Europe may have more freed-up lands by 2050, which could be used for different purposes. For instance, these lands could be left as unmanaged agriculture lands or to be converted into natural grasslands and forests (e.g. afforestation/reforestation). **In our 2050 simulation based on the EUCalc *'Behaviour and Land-Food'* example pathway, freed-up lands would be allocated to forests in order to maximise the terrestrial carbon pool potential**. Figure 33 shows the GHG emission associated with the Land Use, Land Use Change and Forestry (LULUCF) in the EU for this example pathway. Hence, this sector is fundamental to obtain negative emissions in order to assist Europe achieve a net-zero emissions pathway.

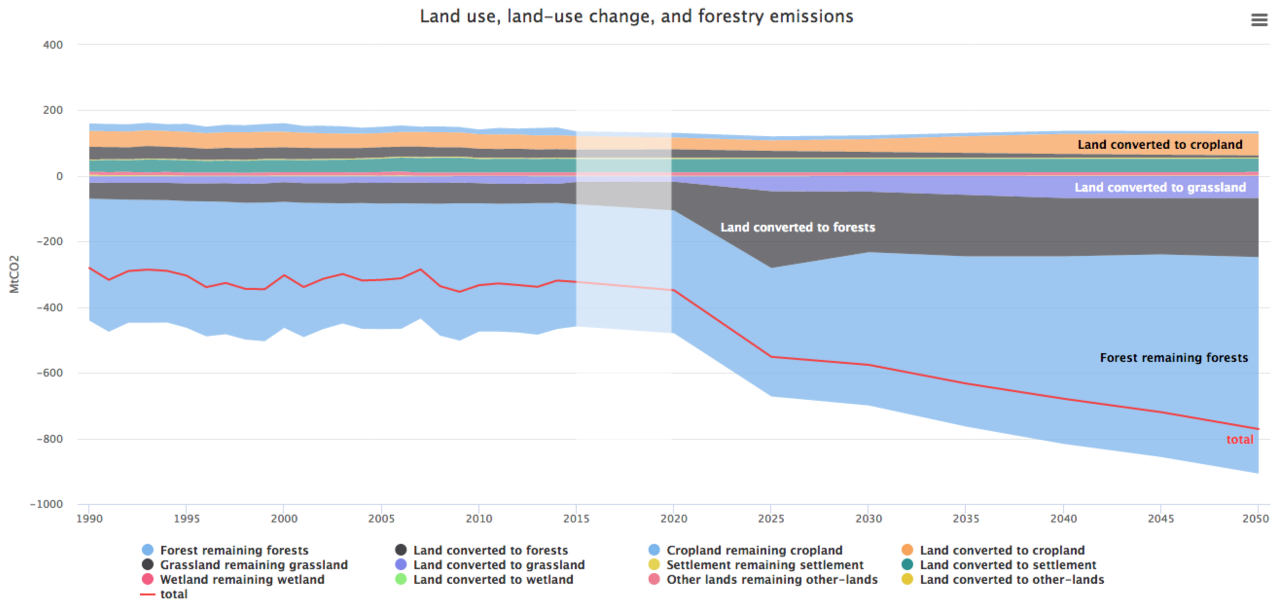


Figure 33: LULUCF GHG emissions in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

4.2 Protecting our biodiversity

Climate change mitigation and biodiversity conservation should be simultaneously addressed whilst aiming at a sustainable future in 2050 under both the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CDB), specially the Aichi conservation targets[11]. Among several important issues that must be addressed in the biodiversity agenda, two important areas also related to climate change mitigation are the proportion of area set aside for nature conservation and the type of land use for habitat restoration in Europe.

How much land area should we set aside for biodiversity protection?

The EUCalc provides the option to set aside areas for biodiversity protection according to different proportions and time frames (e.g. 2020, 2030, 2050). **In our 2050 simulation under the *'Behaviour and Land-Food'* example pathway, priority is given to agriculture and food production, with approximately 17% of the territory of each EU Member State would be set aside for nature in line with the CBD Aichi target 11**.

Aerial Photography of Pine Trees on the Mountain by Creative Vix

However, further benefits for biodiversity could be obtained by setting aside 50% of the territory of each EU Member State, drawing firstly from natural habitats and then looking at the level of restoration necessary in agricultural habitats, contributing to climate change mitigation and adaptation, and to combating desertification (CBD Aichi conservation target 15). This would significantly increase the level of land preservation, whilst also considering potential impacts of climate change on plants (habitats) using the proposed 'Plan for Nature, People and the Economy' (EC, 2017, ref. COM(2017)198) and potential CBD 2030 goals, along with the E.O. Wilson's proposed 'Half for Nature'[12].

[11] See more about the UN CBD Aichi targets at: https://www.cbd.int/sp/targets/
[12] For further information on the Half-Earth project, access: https://eowilsonfoundation.org/

What type of land will be used for habitat restoration?

As conservation levels increase, it may be necessary to restore natural habitats by converting some agricultural lands into protected areas or by setting aside lands that are currently under forestry use, thus reducing timber harvested. **By 2050, under the *'Behaviour and Land-Food'* example pathway, protected areas would be mainly taken from forestlands, i.e. without affecting food production**. On the other hand, converting agricultural lands for habitat restoration would help reduce GHG emissions from the agricultural sector, whilst also enhancing carbon sink through LULUCF.

4.3 Water management

Water management was also assessed in the calculator, **providing simulations for water stress map per EU Member State, as well as water withdrawal and consumption per sector**. Figure 34 and Figure 35 show the expected withdrawal and consumption of water rate under the EUCalc *'Behaviour and Land-Food'* example pathway. The energy sector would remain as dominant in terms of water withdrawal, particularly for cooling in thermopowers, whereas irrigation would remain as the dominant sector in terms of water consumption.

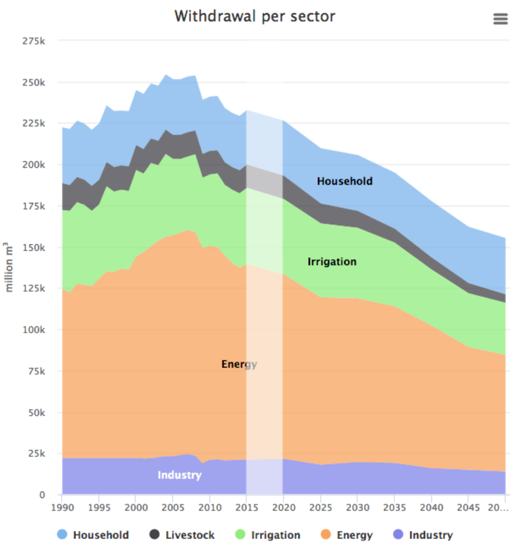


Figure 34: Water withdrawal per sector in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

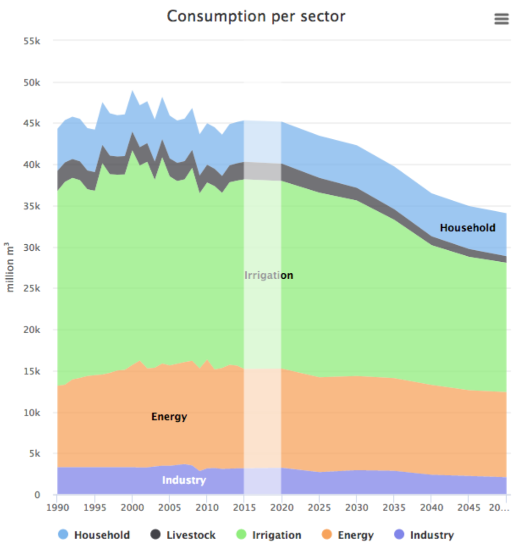


Figure 35: Water consumption per sector in the EU, under the EUCalc 'Behaviour and Land-Food' example pathway.

5 Boundary Conditions

The EUCalc pathways for climate change mitigation are based on some boundary conditions, such as demographics and long-term GHG emissions projections (after 2050), the domestic supply (versus imports) of food, product manufacturing, and material production, as well as constraints regarding the mitigation efforts at global level and the discount factor assumed for financial flows.

5.1 Changes in the European population

How many people will live in what is today the EU28+Switzerland in 2050?

In 2015 there were 516.8 million people, but by 2050 this number may either decrease to about 500 million people or increase to approximately 542 million people. In the scenario simulations already made above (i.e. 'EU Reference', 'Key behaviours', and 'Behaviour and Land-Food'), a recovering fertility for Europe would take place, increasing to 1.65 children per woman, whilst also achieving a decrease in mortality rates, leading to an increase in life expectancy at birth, for both women (87.5 by 2050) and men (82.8 years by 2050), aligned with the projection shown in Eurostat (2018). Additionally, all countries would have a positive net migration (more immigration than emigration) after 2030.

Will Europeans still live in rural areas in 2050?

In 2015, 72% of the European population lived in urban areas, but this number has been decreasing over time. According to Eurostat (2018), urban areas - defined as cities, towns and suburbs – were home to 72% of the EU28's population; 41% live in cities and 31% in towns and suburbs in 2014. **Over the past 50 years, the urban population has continued to grow with considerable differences in the size and spatial distribution of urban developments between Member States. More compact cities favour less need for transport and have demonstrated to have a significant impact on transport GHG emissions**. Based on IIASA Shared Socio-Economic Pathways (SSPs)[13], by 2050 urban population is expected to increase between 76% (SSP3 urbanization scenario) and 83% (SSP1 urbanisation scenario). In all previous simulations (sections 1 to 4), we assumed that this proportion will be approximately 80% (SSP2 urbanization scenario) of the European population.

5.2 Post-2050 emissions

How will GHG emissions evolve beyond 2050?

Post-2050 GHG emissions scenarios are difficult to predict. However, they are important in order to estimate the approximate impacts from the EU on the increase in the global mean surface temperature by 2100. For example, will emissions continue to increase or decrease by 2100? In the previous simulations (sections 1 to 4), we assumed that they will remain the same as the level reached in 2050. However, under a stronger carbon mitigation effort, this emission could keep decreasing until 2100, for instance, based on the decrease similar to the rate observed between 2035 and 2050.

5.3 Accounting for our relationship with the rest of the world

What will the self-sufficiency ratio and associated carbon leakages (embedded in food products) for domestic food production be in 2050?

The EU international food trade (imports vs. exports) can directly affect GHG emission inside and outside Europe. It is estimated that around 20% to 25% of global CO_2 emissions come from the production of goods that are then consumed in a different country and food products are no exception. The EU's self-sufficiency level (i.e. the production over consumption ratio) is approximately 81% for plant-based food (e.g. grains, vegetables, fruits), and 103% for livestock-based food (meat, milk, eggs). Therefore, Europe is currently a net importer of plant-based food (including animal-feed cakes) and a net exporter of meat. These proportions include direct and indirect (e.g. livestock feed) food consumption. By 2050, the self-sufficiency ratio for plant-based food may vary between 70% to 110%, and for meat-based food between 90% to 120%. In the previous simulations (sections 1 to 4), we assumed a 2050 scenario in which the self-sufficient level for plant based would be 81% (like current levels), whereas for meat-based food the ratio would be 100%.

What impact will the trade of products have on industrial production, energy consumption and GHG emissions in 2050?

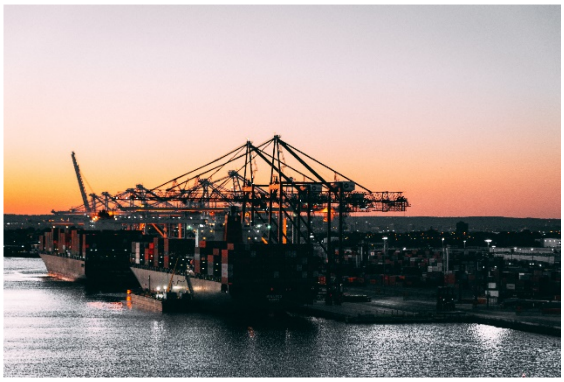
In our 2050 simulations, it was assumed that the 2050 imports of products from demand sectors (buildings, transport, appliances) would follow current trends (i.e. net imports/demand), but may either increase or decrease by approximately 20% (compared to 2015). The historical and projected values of the domestic

[13] See more on the IIASA SSPs at: https://tntcat.iiasa.ac.at/SspDb

share ratios are provided for the economic baseline scenario, generated with the GTAP[14]-EUCalc (computable general equilibrium) CGE model. This GTAP-EUCalc CGE model projects the 2015 world economy, establishing a likely business as usual (BAU) scenario towards 2050, by using reference projections for GDP, population, labour force and total factor productivity obtained from literature.

How many materials will be produced in Europe and how many imported in 2050?

Similar to product manufacturing already mentioned above, here we address the material production that is imported compared to the demand. The projections follow the same GTAP-EUCalc CGE model, with a variation of more or less 20% (compared to 2015). In the simulations here shown (sections 1 to 4), we also assumed that the 2050 imports of materials would follow current trends. **If this value increases, it would generate GHG emissions outside Europe, whereas if it decreases, the associated GHG emissions would be domestically generated, which may not be necessarily the same**.



Port with cranes by Matthis Volquardsen

How will the rest of the world decarbonise their economies by 2050?

Apart from the EU efforts on carbon mitigation, GHG emissions scenarios may follow different pathways, given to impacts coming from other large GHG emitting countries, such as China, the United States, India, Russia, Indonesia, among other nations. In the EUCalc, for example, we suggest a range of pathways, such as: current trends until 2050; Nationally Determined Contributions (NDCs) being met; NDCs being met and further strengthened; and the Paris Agreement being met. For the purpose of the simulations presented in this policy brief, we assumed that current trends would be kept until 2050 at a global scale.

5.4 Discount factor

What discount factor should we use for assessing financial flows regarding carbon mitigation by 2050?

When the discount is high, the future returns on investments are low, which means investments yielding long-term benefits are less profitable. The cost of capital refers to the actual cost of financing business activity through either debt or equity capital. **The discount rate is the interest rate used to determine the present value of future cash flows in standard discounted cash flow analysis**. Another terminology (not used in the EUCalc) is the Weighted Average Cost of Capital (WACC), which is used by many companies as their discount rate when budgeting for a new project. This figure is crucial in generating a fair value for the company's equity. In the EUCalc, the discount factor may vary from 10% a year to 2% year in the most optimistic scenario. In the simulations shown in this policy brief, a discount factor of 7% a year is assumed.

6 Achieving a net-zero GHG emission in Europe

Achieving a net-zero GHG emission by 2050 is a major challenge for Europe. In the context of the European Green Deal (European Commission, 2019) and as demonstrated in the EUCalc *Ambitious* pathway (Figure 36), this would require an extremely ambitious effort across all sectors of the European economy, rather than only focusing on one or two sectors. **This pathway would involve an unprecedent change on the**

[14] GTAP stands for Global Trade Analysis Project.

production and consumption sides, including significant behavioural changes. Moreover, a net-zero GHG emission pathway would only be achievable by obtaining negative emissions in some activities (e.g. land use and biodiversity restoration) in order to counterbalance remaining emissions still coming from other sectors by 2050.

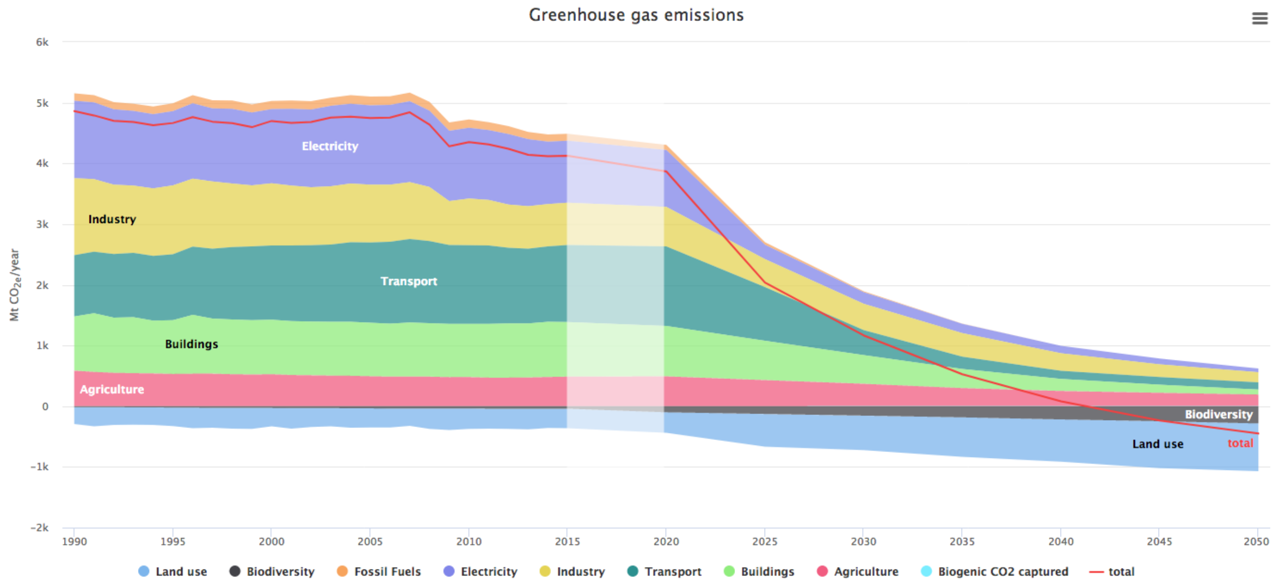


Figure 36: Simulation of an approximate net-zero GHG emissions in Europe, based on the EUCalc 'Ambitious' example pathway.

It is worth noting that this net-zero simulation does not include transboundary effects (imports vs. exports of products), but only the GHG emissions within the EU. However, the EUCalc also offers some simulations on transboundary effects. Clora and Yu (2019) suggest that significant impacts outside Europe can be associated with higher imports, if the rest of the world (ROW) does not increase its carbon mitigation efforts as well. **The recent simulation done using the EUCalc showed that if the EU implements a very ambitious carbon mitigation strategy, the European exports to foreign countries would decrease, whereas the imports would increase at the same time in order to keep the market in equilibrium. This would lead to a deteriorated trade balance and the carbon leakage rate[15] would reach approximately 61.5% on average**. This international impact is subject to large uncertainties, given that they depend on the type of product, country of origin, freight distance, geographical conditions, production costs, international tariffs, among several other variables. International land use impacts were also estimated by Strapasson et al. (2016) for the EU using 2050 Calculators[16], showing that an internal reduction of GHG emissions (e.g. by increasing forestland area inside Europe, whilst also increasing food and meat imports) may lead to high GHG emissions and land use footprint outside Europe, depending on how mitigation efforts are implemented worldwide. As a result of these simulated changes in external trade flows in addition to modifications occurring to domestic and external production and consumption structures, a sizeable share of the EU emission reductions in the most ambitious EUCalc scenarios may be counterbalanced by increased emissions in the ROW (assuming the latter does not take similar actions). Decarbonization efforts by the EU alone cannot reduce global emission effectively. Consequently, concerted actions by the world are needed, if significant levels of carbon leakage are to be avoided and global GHG reductions realized. Moreover, there is an urgent need to carefully balance potentially conflicting policy options for supporting decarbonization efforts in the EU, safeguarding national

[15] The carbon leakage reflects the change in emissions abroad against the emissions reduction within the EU.

[16] See a full list of 2050 Calculators for several nations at: https://www.gov.uk/guidance/international-outreach-work-of-the-2050-calculator

industries under transition and incentivizing the ROW to join climate effective worldwide decarbonization efforts.

In addition to the demonstrations shown in this policy brief, the EUCalc can provide several other pathways and insights towards a fair and just net-zero emissions in Europe by 2050. For those interested in learning more about the EUCalc, the authors of this policy brief would like to encourage them to consult the technical documents available on the EUCalc project website for additional information. Similarly, they are encouraged to also run their own scenarios online using the EUCalc Transition Pathways Explorer.

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About the author:

Dr Alexandre Strapasson is an Honorary Research Fellow at Imperial College London, working on energy, land use and environmental sciences. He is also a Visiting Lecturer at IFP School in France, and an international consultant. Prior to this, he was an Associate Fellow at Harvard University, and one of the lead modellers of the Global Calculator, having contributed to the EUCalc as well.

Dr Onesmus Mwabonje is a Research Fellow at Imperial College London. He has combined academic and industrial experience in application of Life Cycle Assessment (LCA) to supply chains for biofuels, bioenergy and biorefineries to both UK and EU policy requirements. Onesmus has worked on the coordination of the EUCalc module for land & food, and interactions with other sectors.

Dr Jeremy Woods is a Reader in Sustainable Development at Imperial College London, where he is also Co-Director of ICEPT (Centre for Energy Policy and Technology). He works on the interplay between development, land use and the sustainable use of natural resources. Jeremy has been involved in the coordination of the EUCalc and, previously, contributed in the development of the Global Calculator as well.

Dr Gino Baudry is a Research Associate at Imperial College London, working on Energy Economics. His research aims at developing methodological frameworks to foster stakeholder's involvement & participation, combining energy modelling with user-friendly interfaces for the design and implementation of sustainable climate policy. He worked as the EUCalc lead modeller for land & food.

Further information on the EUCalc project:

The EUCalc project aims at providing a highly accessible, user-friendly, dynamic modelling solution to quantify the sectoral energy demand, greenhouse gas (GHG) trajectories and social implications of lifestyle and energy technology choices in Europe.

The novel and pragmatic modelling approach is rooted between pure complex society-energy systems and integrated impact assessment tools. The EUCalc model with its user interface - the Transition Pathways Explorer - has been designed to be both accurate but also accessible to decision-makers and practitioners. It covers all sectors and can be used by one or many people. The model is also open source so that experts can refine the model itself. The tool will have an e-learning version, the "My Europe 2050" tool as well as a Massive open online course (MOOC). See more on the EUCalc project, its scientific reports and all other outputs and access the Transition Pathways Explorer at:

www.european-calculator.eu

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EUCalc partners:

Potsdam Institute for Climate Impact Research

Imperial College London

Climact SA

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University of Copenhagen

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University of East Anglia
Tyndall Centre for Climate Change Research

PANNON Pro Innovations Ltd.

Climate Media Factory UG

T6 Ecosystems S.r.l.

SEE Change Net Foundation

Delft University of Technology

Policy Briefs - Pathways towards a European Low Emission Society

The Policy Briefs on Pathways towards a European Low Emission Society, summarises key finding of the EUCalc project with a clear policy orientation, which provides practical climate change mitigation insights to both EU and individual Member States decision-makers. These policy briefs cover the following topics:

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Find out more:

Potsdam Institute for Climate Impact Research (PIK)
Telegraphenberg A 31
14473 Potsdam – Germany

Prof. Dr. Jürgen Kropp
E-Mail: nsp@pik-potsdam.de
www.european-calculator.eu
Twitter: @EU_Calculator

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